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Performance Evaluation of LTE-Advanced Carrier Aggregation

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ABSTRACT OF THE
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Carrier Aggregation (CA) is an essential technology component in LTE-Advanced (LTE-A). CA is capable of combining up to five Long Term Evolution (LTE) carriers to be used for multicarrier transmission in both downlink and uplink. CA provides increased throughputs, additional capacity and possibilities for load balancing.

This thesis presents the key features of CA. Furthermore, the results from CA performance measurements are analyzed and presented. The measurements were conducted in live network to evaluate the end-user experience. The objective was to determine whether CA is capable of delivering the performance that could be theoretically expected.

The performance was measured in LTE-A radio network using 2×20 MHz bandwidth with 2×2 MIMO configuration and Category 6 User Equipment (UE). Only downlink CA was measured, since uplink CA capable UEs were not commercially available. The performance was evaluated with stationary and mobility measurements.

The results indicate that CA is capable of providing the expected performance gain. In good radio conditions the maximum downlink throughput is close to the 300 Mbit/s. Furthermore, CA performs well in poor radio conditions. The performance gain can be more than 100 %, if the additional carrier is on an unused band.

In CA, a secondary component carrier is configured for the UE, in addition to the primary carrier. The operation is performed in connected state either after connection setup or radio handover. The delay in secondary carrier addition was measured to evaluate the impact on user experience. The results indicate that the secondary carrier addition after connection setup or handover is sufficiently fast, and do not have an impact to the user experience.

Keywords: LTE, LTE-Advanced, Carrier Aggregation, CA, component carrier, MIMO, field measurement

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SÄHKÖTEKNIIKAN KORKEAKOULU

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TIIVISTELMÄ

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Kanavien yhdistäminen (engl. Carrier Aggregation) on oleellinen tekniikka edistyneessä Long Term Evolution järjestelmässä. Sen avulla on mahdollista yhdistää enintään viisi LTE taajuutta käytettäväksi monikanavaiseen ala- ja ylälinkin lähetykseen. CA mahdollistaa aiempaa suuremmat siirtonopeudet, lisää verkon kapasiteettia sekä antaa mahdollisuuden kuormanjakoon eri taajuuksien välillä.
Tässä työssä esitellään CA:n keskeiset ominaisuudet. Lisäksi CA:n suorituskykymittauksien tulokset on analysoitu ja esitelty. Mittaukset toteutettiin operaattorin tuotantoverkossa, jotta loppukäyttäjän saamaa kokemusta on mahdollista arvioida. Tavoitteena oli selvittää, pystyykö CA tarjoamaan sellaista suorituskykyä, jota voidaan teorian perusteella odottaa.
Suorituskykyä mitattiin LTE-radioverkossa käyttäen 2×20 MHz kaistanleveyttä ja 2×2 MIMO:n kokoonpanoa sekä kategorian 6 päätelaitetta. Mittaukset suoritettiin vain alalinkissä, sillä ylälinkin CA-kykyisiä päätelaitteita ei ollut kaupallisesti saatavilla. Suorituskykyä on arvioitu sekä piste- että mobiliteettimittauksilla.
Tulokset osoittavat, että CA pystyy tarjoamaan oletetun suorituskyvyn parannuksen. Hyvissä radio-olosuhteissa maksimi datanopeus alalinkissä on lähes 300 Mbit/s. Lisäksi CA toimii hyvin myös huonoissa radio-olosuhteissa. Suorituskyvyn parannus voi olla enemmän kuin 100 %, jos lisätty toinen kanava on vähemmän käytetyllä taajuuskaistalla.
CA:ssa toissijainen kanava konfiguroidaan päätelaitteelle ensisijaisen lisäksi. Operaatio suoritetaan yhteystilassa joko yhteyden muodostamisen tai solunvaihdon jälkeen. Toissijaisen kanavan lisäämisen aiheuttama viive mitattiin, jotta sen vaikutus käyttökokemukseen voitiin arvioida. Tulokset osoittavat, että toissijaisen kanavan lisääminen yhteyden muodostamisen tai solunvaihdon jälkeen on riittävän nopea operaatio, eikä sillä ole vaikutusta käyttökokemukseen.

Avainsanat: LTE, LTE-Advanced, kanavien yhdistäminen, CA, komponenttikanava, MIMO, kenttämittaus

Preface

This thesis was done for TeliaSonera between September 2014 and April 2015.

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Contents

Symbols and Abbreviations

Symbols

Δ	Change in given variable
$\times$	Multiplication
λ	Wavelength
ρ_{xy}	Correlation coefficient
σ_x	Standard deviation
σ_{xy}	Covariance

Abbreviations

3GPP	Third Generation Partnership Project
ACK	Acknowledgement
ANR	Automatic Neighbor Relations
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BER	Bit Error Rate
BLER	Block Error Rate
CA	Carrier Aggregation
CC	Component Carrier
CCCH	Common Control Channel
CCS	Cross Carrier Scheduling
CE	Control Element
CIF	Carrier Information Field
CN	Core Network
CoMP	Coordinated MultiPoint
CQI	Channel Quality Indicator
CS/CB	Coordinated Scheduling and Beamforming
CSG	Closed Subscriber Group
CSI	Channel State Information
DCCH	Dedicated Control Channel
DCI	Downlink Control Information
DFT	Discrete Fourier Transform
DL-SCH	Downlink Shared Channels
DRB	Data Radio Bearer
DRX	Discontinuous Reception
DSL	Digital Subscriber Line
DTCH	Dedicated Traffic Channel
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EARFCN	E-UTRAN Absolute Radio Frequency Channel Number
EIRP	Equivalent Isotropic Radiated Power
eNodeB	Evolved Node B
EPC	Evolved Packet Core

EPDCCH	Enhanced Physical Downlink Control Channel
EPS	Evolved Packet System
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GERAN	GSM/EDGE Radio Access Network
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTP	GPRS Tunnel Protocol
HARQ	Hybrid Automatic Repeat reQuest
HetNet	Heterogeneous Networks
HO	Handover
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
ICIC	Inter-cell Interference Coordination
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
JT	Joint Transmission
L1	Layer 1
L2	Layer 2
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
MCCH	Multicast Control Channel
MCH	Multicast Channel
MCS	Modulation and Coding Scheme
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MPR	Maximum Power Reduction
MTCH	Multicast Traffic Channel
MU-MIMO	Multi-user MIMO
NACK	Negative Acknowledgement
NAS	Non-Access Stratum
OCC	Orthogonal Cover Code
OFDMA	Orthogonal Frequency Division Multiple Access
P-GW	Packet Data Network Gateway
PBCH	Physical Broadcast Channel

PCCH	Paging Control Channel
PCell	Primary Cell
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PCI	Physical Cell Identifier
PCRF	Policy and Charging Resource Function
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PDU	Payload Data Unit
PHICH	Physical Hybrid ARQ Indicator Channel
PHR	Power Headroom Report
PMCH	Physical Multicast Channel
PMI	Precoding Matrix Indicator
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PS	Packet Switched
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R-PDCCH	Relay Physical Downlink Control Channel
RAB	Radio Access Bearer
RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RI	Rank Indicator
RLC	Radio Link Control
RN	Relay Node
RNTI	Radio Network Temporary Identifier
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RS	Reference Signal
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
S-GW	Serving Gateway
SAE	System Architecture Evolution
SC-FDMA	Single Carrier Frequency Division Multiple Access

SCell	Secondary Cell
SCTP	Stream Control Transmission Protocol
SDU	Service Data Unit
SGSN	Serving GPRS Support Node
SIB	System Information Block
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
SON	Self-Optimizing/Organizing Network
SR	Scheduling Request
SRB	Signalling Radio Bearer
SRS	Sounding Reference Signal
SU-MIMO	Single-User MIMO
TA	Tracking Area
TBS	Transport Block Size
TDD	Time Division Duplex
TE	Terminal Equipment
TM	Transmission Mode
TPC	Transmission Power Control
TTI	Transmission Time Interval
UCI	Uplink Control Information
UDP	User Datagram Protocol
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL-SCH	Uplink Shared Channel
USIM	Universal Subscriber Identity Module
UTRAN	Universal Terrestrial Radio Access Network
VCID	Virtual Cell Identity
VoIP	Voice Over IP
VoLTE	Voice Over LTE
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

1 Introduction

The global mobile data traffic has grown tremendously during the last few years and the growth is expected to continue in the future. In the coming years, the emphasis will be in providing video and voice services over packet switched mobile networks. It has been estimated that mobile video streaming will increase 13-fold between 2014 and 2019 [1]. There will be increased demand in high capacity mobile networks. At the same time it is more cost efficient to provide the Internet services wirelessly, which will increase the number of mobile data users [1] [2]. While the 3GPP Release 8 Long Term Evolution (LTE) networks have been deployed rapidly, more advanced solutions are needed.

LTE-Advanced Carrier Aggregation (CA) is one possible solution for the operators to manage global mobile network traffic growth. CA is a technique that is capable of combining multiple LTE carriers. It enables deploying high capacity and performance radio networks. The network vendors and operators have been increasingly interested on CA recently. The technology has already been trialed and implemented in several countries [3].

1.1 Objectives and Research Scope

This thesis focuses on studying the practical performance of one of the key features of LTE-Advanced: Carrier Aggregation.

The principal research questions are the following. Is Carrier Aggregation capable of delivering the performance that can be theoretically expected? What is the performance gain compared to Release 8 LTE? The practical performance of CA is evaluated in different environments by comprehensive field measurements. Furthermore, the performance measurements are conducted in operator's live LTE network, which should provide results comparable to the actual user experience.

Presently, only downlink Carrier Aggregation solutions exist, due to transmitter implementation challenges in the User Equipment (UE). Also, the current CA solutions consist of only two component carriers. Therefore, the performance evaluation focuses on downlink. The performance of a radio network system is often evaluated with throughput measurements, which is the main method in this paper as well. The research scope also includes investigating the behavior when data connections are established and mobility management is performed with CA. The thesis focuses on Frequency Division Duplex (FDD) version of LTE, while Time Division Duplex (TDD) is not discussed.

Reader should be familiar with the basic principles of the mobile communication systems and packet switched networks. However, the fundamentals of LTE networks are presented in this thesis to give background information for LTE-A and CA functionality.

1.2 Research Methods

This thesis provides a literature review on LTE and LTE-Advanced. While the main focus of this thesis is on LTE-A, the basic knowledge of LTE is provided to understand the functionalities in LTE-A. Carrier Aggregation is one of the key features in LTE-A and it is also the primary topic of this paper. The theoretical functionality of CA is discussed in detail. The main sources of information in the literature review are the 3GPP technology specifications along with few recognized reference books and research papers from the field of radio access networks.

The empirical part of the thesis consists of field measurements conducted in Helsinki metropolitan area. The method was chosen since it corresponds to the actual user experience and also because there are not many such research on Carrier Aggregation available. Rather extensive field measurements were conducted to explore the behavior of CA in various environments and to clarify the performance gain of CA compared to Release 8 LTE. Additionally, the performance of CA in connection establishment and in basic mobility situations was evaluated.

The reliability and significance of the results are also discussed. The analysis is based on previous research, such as simulations, laboratory tests and field measurements.

1.3 Structure of the Thesis

The overview on LTE is presented in Section 2. Firstly, it covers the design goals and system architecture for the Evolved Packet System. Secondly, the LTE physical layer aspects are discussed, including multiple access techniques and MIMO in Section 2.3. Thirdly, the radio protocol stack of LTE is covered in Section 2.4, followed by introduction to the channel structure. Lastly, the basic concepts of LTE mobility are presented in Section 2.6.

LTE-Advanced is introduced in Section 3. The requirements set by IMT-Advanced framework are presented in Section 3.1, followed by the offered solutions and features of LTE-Advanced in Section 3.2.

The last theory part focuses on Carrier Aggregation in Section 4. The impact of CA on radio protocols is presented for both downlink and uplink. The emphasis is on downlink functionality as most of the field measurements are also conducted in downlink. Cell management and CA mobility are discussed in Section 4.5. The rest of the section covers the performance expectations of CA, possible band combinations and the future evolution of LTE-A and radio networks in general.

Section 5 covers the actual performance evaluation. Firstly, the measurement setup is presented and the utilized carrier frequencies are compared to provide understanding on studying the measurement results. The stationary measurement cases and results are illustrated in Section 5.3 and the mobility measurements are presented in Section 5.4. The results are evaluated and compared to the other studies in Section 5.5.

Finally, the Section 6 concludes the thesis and provides proposals for further research.

2 Long Term Evolution

The system architecture and basic functionality of Long Term Evolution are presented and discussed in this section. The design goals and quick glance to the LTE specification versions are given in Section 2.1. The next part (Section 2.2) covers the Evolved Packet System (EPS) architecture and describes the network elements. The physical layer of LTE is discussed in Section 2.3, including multiple access schemes, introduction to MIMO, along with brief introduction to modulation and frame structures. The next two sections present the radio protocols (Section 2.4) and LTE channel structure (Section 2.5). Lastly, the concept of mobility is discussed in Section 2.6.

2.1 LTE Design Principles

The third generation High Speed Packet Access (HSPA) enabled the voice dominated mobile networks to transform into packet data dominated networks. 3GPP Long Term Evolution (LTE) is namely an evolution to that technology. The development was driven by increasingly growing mobile packet data traffic.

LTE introduced new system architecture and multiple access techniques, which improved the system performance. LTE is also fully packet switched technology. Due to extensive changes, the terminals that support only earlier 3GPP generations cannot access to LTE network. However, LTE has good interoperability capabilities towards HSPA, WCDMA and GSM.

Other design targets for LTE were the support for future enhancements in the core network, such as IP Multimedia Subsystem (IMS). The motivation for System Architecture Evolution (SAE) was to decrease the latencies and access delay by reducing the number of network elements. The resource and mobility management functionalities were implemented at the base station, which removed the need for separate control elements.

Compared to earlier generations, LTE aimed for increasing spectral efficiency 2–4 times. That required new multiple access schemes. With streamlined architecture and improved spectral efficiency, the targets for data rates were also higher than before: 100 Mbit/s for the downlink and 50 Mbit/s for the uplink. Also, the frequency allocation was specified to be more flexible. [4]

The 3GPP introduces new specifications for Radio Access Technologies (RAT) in sequential versions, also referred as *Releases*. Release 8 included the first LTE specification and Release 10 introduced some of the LTE-Advanced features, including CA. Table 1 summarizes the latest releases and key features.

2.2 Evolved Packet System

Evolved Packet System (EPS) consists of LTE radio access network (E-UTRAN) and the core network (EPC). The most significant change the from earlier generations is that EPS does not need to support circuit switched operation. EPS is fully a packet switched system. The architecture has been streamlined in such way that

Table 1: 3GPP Releases and their key features [5]

Release	Frozen	Features
Rel 8	Mar 2009	LTE specification
Rel 9	Mar 2010	Minor improvements to e.g. MIMO and SON
Rel 10	Jun 2011	LTE-Advanced, uplink MIMO
Rel 11	Mar 2013	LTE-A improvements, e.g. CoMP
Rel 12	Mar 2015	Improvements to e.g. CA and HetNets
Rel 13	2016 (est.)	Further improvements to CA and MIMO

there are less nodes between radio network and packet gateways. In this type of flat architecture the base stations are directly connected to the management entity and to the gateway. [4]

The EPS architecture, including its network elements and interfaces are presented in Figure 1 and described in the following sections.

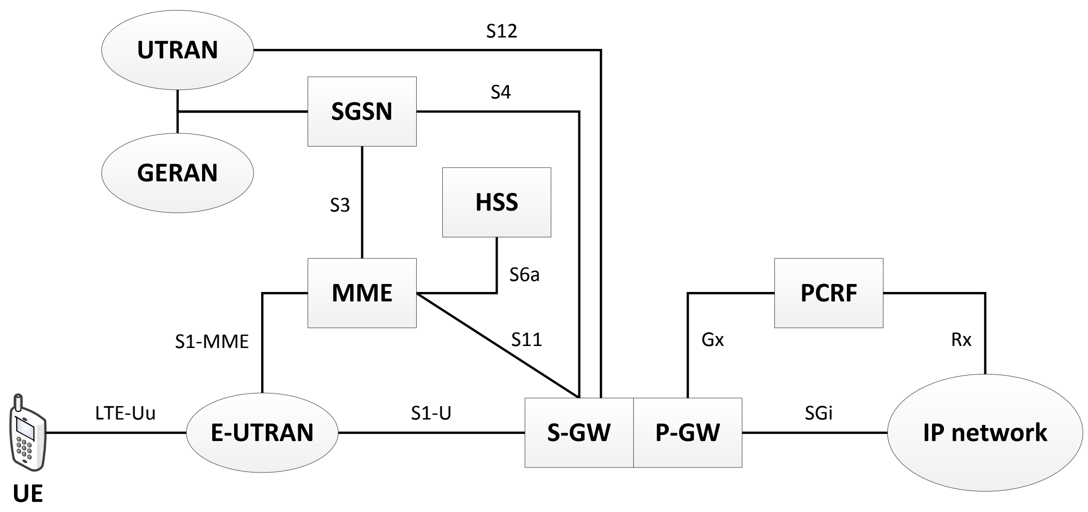


Figure 1: Evolved Packet System architecture [6]

2.2.1 UE and E-UTRAN

Evolved Universal Terrestrial Radio Access Network (E-UTRAN) consists of only one network element: evolved Node B (eNodeB), which refers to the base station. Additionally, the user needs specialized terminal to access E-UTRAN, logically referred as User Equipment (UE).

User Equipment (UE) refers to the mobile terminal that end user uses for communication. Typical devices are mobile phones, tablets, laptops and USB-modems. The device is called Terminal Equipment (TE). UE also includes

Universal Subscriber Identity Module (USIM). USIM is placed on a removable smart card: Universal Integrated Circuit Card (UICC). USIM is used to identify and authenticate the user and secure connections. UE is a platform that is capable of setting up, maintaining and removing the communication links towards the network with appropriate signalling messages exchange and reporting. [4]

Evolved Node B (eNodeB) is a radio base station, which is in control of all radio related functions in E-UTRAN. There are no additional controllers for eNodeBs as they are directly connected to the EPC. The eNodeB is a termination point for all radio protocols towards the UE and all connections between eNodeB and EPC are based on IP. On user plane, the eNodeB performs IP header compression and user data encryption [7]. On control plane, the eNodeB is responsible for allocating resources for the users according to traffic situation and required Quality of Service (QoS). The eNodeB also handles major part of the UE mobility management. It has the intelligence to analyze UE radio measurements and to make handover decisions accordingly. In E-UTRAN, eNodeB is connected to UEs and other eNodeBs via X2 interface, and to MME and S-GW in EPC. [4]

2.2.2 Evolved Packet Core

The LTE core network is referred as Evolved Packet Core (EPC). It consists of the following logical elements. A network manufacturer may choose to implement more than one logical element into one physical device. E.g. the control entities (SGSN and MME) [8] can be combined and also the gateway elements [9].

Mobility Management Entity (MME) is the main control element in EPC. It operates the control plane and is not involved in the user plane. MME is responsible for Non-access Stratum (NAS) signalling (see Section 2.4) towards the UE, and authentication and security functions [7]. Other main task of the MME is the mobility management in inter-MME and inter-RAT handovers. MME is also involved in all other handovers by updating the control plane connection to the target eNodeB. MME is responsible for roaming function in the network [7]. In idle state, the UE reports its location periodically to the MME and instantaneously in case of Tracking Area change. Thus, MME keeps track of the location of every user. MME also has the information of subscriber profiles in collaboration with HSS. MME selects the correct gateway for the user. MME is connected to multiple eNodeBs in E-UTRAN. In EPC it is connected to other MMEs (possibly), HSS and S-GWs. [4]

Home Subscriber Server (HSS) is the subscription data repository for permanent user data, and also for user location on MME level. It stores the master copy of subscriber profile, including the user permissions to use e.g. data or roaming. HSS stores user encryption keys. HSS is connected to each MME in the network and it stores the current MME and P-GW for each user. [4] [10]

Serving Gateway (S-GW) is a centralized gateway for user plane data. It deploys a tunnel for user data from E-UTRAN towards IP networks. E-UTRAN is connected directly to S-GW for user plane access. S-GW is also connected to MME and P-GW that provide necessary control information for packet routing and forwarding. S-GW has minor role in control plane functions as it is responsible only for its own resources. User plane data is relayed between P-GW and E-UTRAN. If UE enters idle state, the data path in S-GW terminates. A new data path has to established either via paging procedure or a request from UE. S-GW monitors the data flow in tunnels and may collect information related to accounting and user charging. While there might be multiple S-GWs in the system, one S-GW is serving one UE at the time. UE might change S-GW within a handover and the change is controlled by MME. [4] S-GW also serves as a local mobility anchor in inter-eNodeB and inter-3GPP handovers. [7]

Packet Data Network Gateway (P-GW or PDN-GW) provides the edge router function between EPC and external packet data networks. It is the highest level mobility anchor in EPS and is the IP attachment point for the UE. P-GW is a centralized function in the core network. P-GW allocates the IP address for UE using DHCP server functionality. The IP address is allocated each time the UE requests for a packet data connection. P-GW is connected to S-GW through S5/S8 interface and if the interface is based on GTP, the P-GW maps the IP data into GTP tunnels (bearers). The bearers are established based on a request either from S-GW or PCRF. P-GW performs user based packet filtering and lawful interception if needed [7]. It is capable of monitoring the user data flows for accounting. P-GW is connected to PCRF through Gx interface. [4]

Serving GPRS Support Node (SGSN) is used to establish a mobility management context for 3GPP UTRAN and GERAN. It creates a Packet Data Protocol (PDP) context for user data connections towards S-GW. SGSN is connected to S-GW via S4 interface and to MME via S3 interface. [10] More information on interworking with other radio access technologies can be found e.g. from [4].

Policy and Charging Rules Function (PCRF) handles policy and charging control functions in EPC. It defines the QoS profiles for UE data bearers. PCRF provides policy and charging control rules for each new bearer that is established. The rules are provided for P-GW (connected via Gx interface) and S-GW that employ them to data connections. PCRF also performs required security procedures for policy control. [4] [11]

2.3 Physical Layer

The basic principle in LTE physical layer is that resources are shared dynamically among the users. No user receives dedicated resources. The principle is comparable to one in the Internet and packet switched networks in general. There is a variety of techniques for multiple users to simultaneously access the radio system. LTE multiple access method differs from earlier 3GPP generations. Downlink multiple access in LTE is based on Orthogonal Frequency Division Multiple Access (OFDMA) and uplink multiple access is based on Single Carrier Frequency Division Multiple Access (SC-FDMA).

2.3.1 OFDMA and SC-FDMA

The principles of OFDMA have been known since 1950s and it has been widely used in wireless communications. OFDMA implementation is based on the use of Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT) to move from time domain to frequency domain and back. Practical solutions use the Fast Fourier Transform (FFT) to change signal from time domain to frequency domain. The inverse FFT (IFFT) transforms the signal from frequency domain to time domain. If a sinusoidal waveform is transformed with FFT it results in one peak at the corresponding frequency and zero elsewhere. A rectangular waveform produces several peaks. An impulse as an input for FFT would produce peak on all frequencies. One desired property of the FFT operation is that the transform is lossless in both directions, assuming sufficient sampling rates and word lengths.

In regular frequency division multiple access, different users occupy different carriers or subcarriers to access the system simultaneously. The signal waveforms have to be created so that they will not interfere each other. To use the bandwidth efficiently there cannot be wide guard bands between subcarriers. In case of multi-carrier transmission the data is divided on different sub-carriers of one transmitter. There is a constant spacing between the adjacent carriers. This obviously creates inefficiency in the bandwidth utilization. Guard band problem is addressed by choosing the system parameters in such way that the different transmissions are orthogonal to each other. Subcarriers should be created in such way that they do not cause interference, but can still overlap each other to achieve better efficiency. The method is referred as Orthogonal Frequency Division Multiplexing (OFDM). Each of the possible sub-carriers is selected from a set in which the other sub-carriers have zero-value in frequency domain and the selected carrier has maximum value at the sampling instant. [4]

The motivation for OFDMA:

- Good performance in frequency selective fading channels
- Low complexity of base-band receiver
- Good spectral properties and handling of multiple bandwidths
- Link adaptation and frequency domain scheduling
- Compatibility with advanced receiver and antenna technologies

The challenges of OFDMA:

– Tolerance for frequency offset. 15 kHz subcarrier spacing is used in LTE to overcome this issue.

– The high peak-to-average ratio of transmitted signal. This requires linear amplifiers in transmitters, which have low power conversion efficiency and therefore are not suitable for LTE uplink.

OFDMA receiver has to counter the effect of channel conditions and noise. In LTE a specific Reference Symbols (RS) are used to make estimations of the channel impact on other OFMA symbols. The reference symbols are placed on predetermined locations both in time and frequency domain. Thus, the receiver can adjust the received signal using the estimation and determine the original signal. Typically, a frequency domain equalizer is utilized to revert the channel impact on each sub-carrier. OFDMA frequency domain equalizer multiplies each sub-carrier based on the estimated channel frequency response. [4]

The OFDMA transmitter differs from the HSPA transmitter as the user can occupy any number of subcarriers. The resources are allocated in both time and frequency domain, whereas in HSPA the resources are allocated only in time domain and each user occupies full bandwidth. Therefore, LTE downlink scheduler is more complex than HSPA scheduler. However, the LTE scheduler has the benefit of being capable of allocating users based on channel interference conditions.

In cellular systems it is often beneficial to have maximum power amplifier efficiency to have minimum power consumption. Signal envelope variation causes challenges to this design principle as power amplifier back-off increases. The increased power consumption in mobile device was one of the reasons why OFDMA was not chosen for LTE uplink transmission. [4]

Instead of OFDMA, 3GPP defined SC-FDMA to be used as LTE uplink multiple access method. SC-FDMA has the same good spectral waveform characteristics as OFDMA. Thus, there is no need for guard bands that would reduce the bandwidth available for payload transmission. Cyclic prefix is used to prevent inter-symbol interference as in OFDMA, but it is added between block of symbols. The receiver uses equalizer to counter the inter-symbol interference within a block of symbols.

The uplink transmission takes continuous piece of the spectrum for the user and it is allocated for 1 ms time periods. Increasing the frequency resource for one user increases the data rate. SC-FDMA uses same 15 kHz sub-carrier spacing as OFDMA. Although, SC-FDMA is single carrier transmission by definition, the signal generation phase uses sub-carrier term. In practice, the signalling causes constraints to frequency allocation resolution. Therefore, the frequency resources are allocated in similar method as in downlink direction. The eNodeB facilitates the scheduling and resource allocation between different uplink users. The eNodeB knows which user transmits within a given resource.

Uplink reference symbols are located in the center of the slot. Reference symbols are used by the receiver to precisely estimate the channel impact on the received signal. As only one symbol is transmitted in the time domain, the system has good envelope property and the signal waveform is determined by the modulation method applied. Therefore, SC-FDMA has significantly lower peak-to-average-ratio than

OFDMA. Efficient power amplifiers can be used in transmitters, which results to lower power consumption. In LTE uplink, typically either QPSK or 16QAM are be used as modulation method. The former has lower data rate, but it is less vulnerable to noise and has lower power consumption, which is desirable in mobile devices. The receiver in eNodeB is more complex (compared to OFDMA receiver in the UE) due the use of additional equalizers for terminating inter-symbol interference. However, that is not considered as an issue, since eNodeB has the available computing power to handle the problem. [4]

2.3.2 MIMO

Multiple Input Multiple Output (MIMO) is one of the key concepts in LTE to enhance the throughput and overall performance. LTE Release 8 supports 2×2 and 4×4 MIMO for downlink. Uplink MIMO was not specified until Release 10.

Traditional method to implement multi-antenna scheme is to use *transmit diversity*. The same data is transmitted through two antennas to decrease the effect of fading at the channel. Thus, the system capacity is increased by ensuring the integrity of the signal. [12]

The method to significantly increase system throughput is referred as *spatial multiplexing*. It requires good SNR and multipath propagation environment to perform as expected. In spatial multiplexing, parallel data streams including different data are transmitted simultaneously. If orthogonal streams are used, they would not interfere each other. Transmission power is divided for each signal stream and thus, the received signal power is less than with single stream transmission. Also, the data streams are not doubled and are therefore more prone to error.

The eNodeB needs to know the number of possible spatial layers and the channel quality. More accurate knowledge is not required. UE measures channel information from each spatial layer and reports to eNodeB. [12]

2.3.3 Frame Structure

In FDD LTE, the radio frame and subframe structures are the same in both downlink and uplink. The structure of a slot depends on the multiple access method, and therefore it is different in downlink and uplink. Downlink slot includes typically 7 OFDM symbols. If extended cyclic prefix is used, there are 6 symbols per slot. In uplink, the number of symbols depends on the used bandwidth. [13]

Radio frame length is 10 ms and it consists of 10 subframes. The frame structure is presented in Figure 2.

Physical Resource Block (PRB) length is 0.5 ms (one slot) and it contains 12 subcarriers. The subcarrier spacing is 15 kHz, thus the PRB bandwidth is 180 kHz. Resource block structure is illustrated in Figure 3. The eNodeB allocates radio resources in each subframe (1 ms). It is also known as Transmission Time Interval (TTI). Therefore, the minimum allocation for each user is two PRBs. The number of resource blocks depends on available bandwidth. The supported LTE bandwidths are 1.4, 3, 5, 10, 15 and 20 MHz. The minimum bandwidth of 1.4 MHz translates to

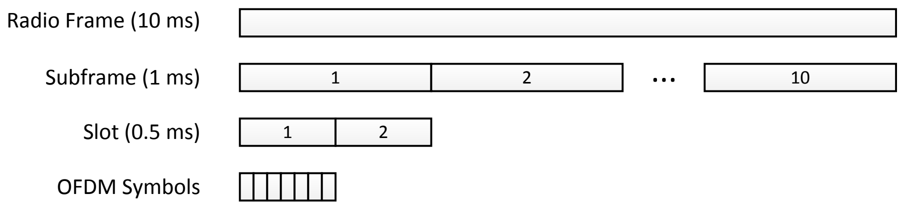


Figure 2: LTE downlink frame structure [13]

6 PRBs including guard bands. Correspondingly, the maximum bandwidth in LTE is 20 MHz, which includes 100 PRBs and the guard bands. [7]

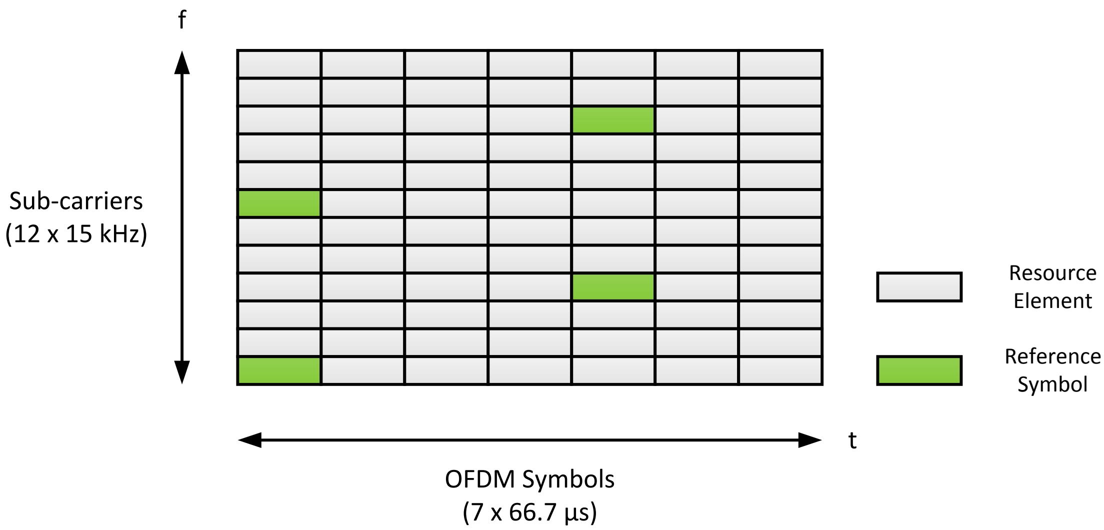


Figure 3: Resource Block structure [7]

2.3.4 Modulation

Modulation refers to process where the carrier signal properties are modified with modulating signal, containing information to be transmitted. More information can be transmitted using higher order modulation scheme. [14] Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) are used to transmit user plane information in LTE.

The modulated signal has 2^m different states and each symbol contains m bits. In QAM, both signal amplitude and phase determine the particular state. QAM can have e.g. 16 or 64 different states. QPSK, 16QAM and 64QAM modulation schemes are employed in LTE. QPSK is the lowest order modulation scheme and it is capable of transmitting 2 bits per symbol. 16QAM can transmit 4 bits per symbol and 64QAM can transmit 6 bits per symbol. [15]

If bandwidth is kept constant, the higher order modulation increases the transmission bit rate. Alternatively, the bandwidth can be decreased while maintaining the bit rate. However, the higher order modulation is more vulnerable to channel noise. Thus, using e.g. 64QAM requires good Signal-to-Noise Ratio (SNR) conditions to reach acceptable bit error rate. In practice, the network selects more robust modulation scheme, if the channel conditions degrade.

In LTE, the same modulation scheme is employed over the entire carrier. In theory, OFDMA allows using different modulation for each subcarrier. However, that is not feasible due to additional signalling required. [4]

The different modulation schemes are visualized in Figure 4.

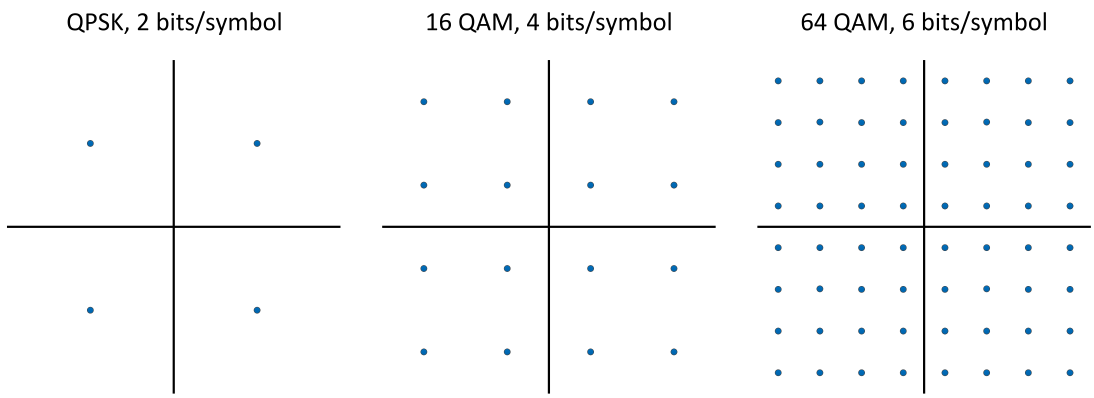


Figure 4: Modulation schemes in LTE [4]

2.4 Radio Protocols

The Evolved Packet System (EPS) protocol structure has changed significantly from the previous 3GPP technologies. EPS relies on the Internet based protocols also for the control plane messaging. The required Internet protocols in EPS are described in this part. Apart from the radio interface, Internet Engineering Task Force (IETF) has mainly specified the protocols used in EPS. The radio interface protocols are specified by 3GPP and they are further discussed and referenced in this section.

LTE radio interface protocols set up, modify and release Radio Access Bearers (RAB) required for carrying the IP data. Radio protocol stacks are somewhat different for the control plane and the user plane, and they are therefore presented separately. The control plane protocol stack is illustrated in Figure 5 and the user plane protocol stack in Figure 6.

The required network elements for control plane are UE, eNodeB and Mobile Management Entity (MME). The air interface between UE and eNodeB is referred as LTE-Uu and the interface between eNodeB and MME is known as S1-MME. [4]

The control plane protocol stack of LTE-Uu interface consists of the following protocol layers: Layer 1 (L1), Layer 2 (MAC, RLC and PDCP) and Layer 3 (RRC).

L1 (Layer 1) is often referred as the physical layer. It includes the used transmission medium and its functionalities (e.g. multiple access method and modulation scheme).

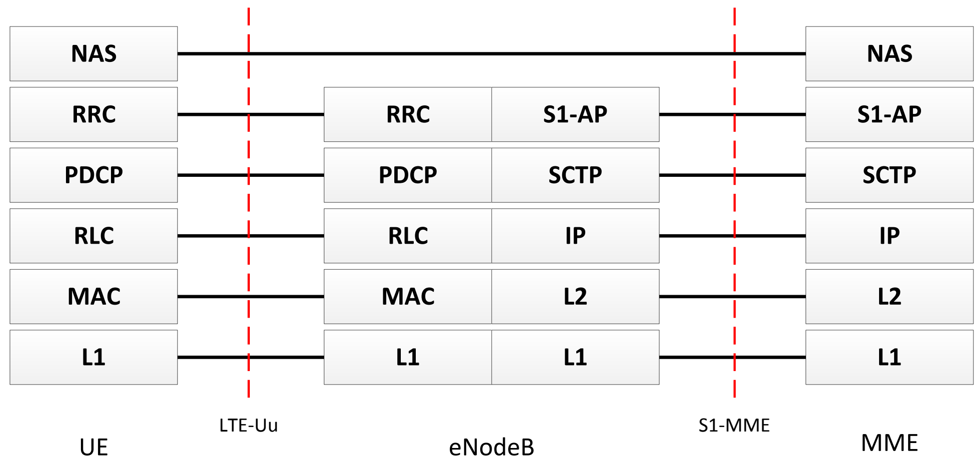


Figure 5: Control plane protocol stack for LTE-Uu and S1-MME interfaces [6]

MAC (Medium Access Control) layer is used to map the logical channels to transport channels. It is also responsible for traffic volume reporting and error correction through re-transmissions (HARQ). Scheduling functions belong to the MAC layer. [16]

RLC (Radio Link Control) layer is connected to MAC layer via logical channels. RLC processes and transfers data units (PDUs towards lower layers and SDUs towards upper layers) between upper and lower layers. The processing includes separating and concatenating data units, and detecting duplicate units. [17]

PDCP (Packet Data Convergence Protocol) is located above RLC layer and its key functionalities are header compression, ciphering user and control plane data, integrity protection and verification. [18]

RRC (Radio Resource Control) is a Layer 3 functionality that is responsible for managing the radio resources of the UE and eNodeB. RRC manages UE connection states, mobility functions, paging, cell management, and establishing and releasing user Data Radio Bearers (DRB). [19]

NAS (Non-access Stratum) is a signalling protocol between UE and MME. It is used to support UE mobility (e.g. tracking area updates) and to support establishing and maintaining IP connectivity between UE and P-GW. [20]

The control plane protocol stack of S1-MME interface follows the Internet protocol model [21] and it consists of the following protocol layers:

L1 (Layer 1) is often referred as the physical layer. It provides a transport medium to the upper layers and in the context of EPS it is typically implemented with optical fiber.

L2 (Layer 2) refers to the medium access technology provided for the Internet Protocol. It handles the IP packet encapsulation. In EPS the typical L2 technology is Ethernet.

IP (Internet Protocol) layer handles and reassembles incoming IP datagrams and chooses the next node for outgoing IP datagrams. Essentially, IP is the routing function in any data network. [21]

SCTP (Stream Control Transmission Protocol) is the transport protocol for EPS control plane messages. It offers reliable transport stream for the control plane on top of IP layer. [22]

S1-AP (S1 Application Protocol) is a protocol, which provides signalling service between eNodeB and MME. S1-AP has functions such as RAB management, UE capability indication, paging and NAS signalling transportation. [23]

The required network elements for user plane are UE, eNodeB and packet gateway (S-GW/P-GW). The air interface is known as LTE-Uu and the interface between eNodeB and S-GW is referred as S1-U. Figure 6 presents the user plane protocol stack.

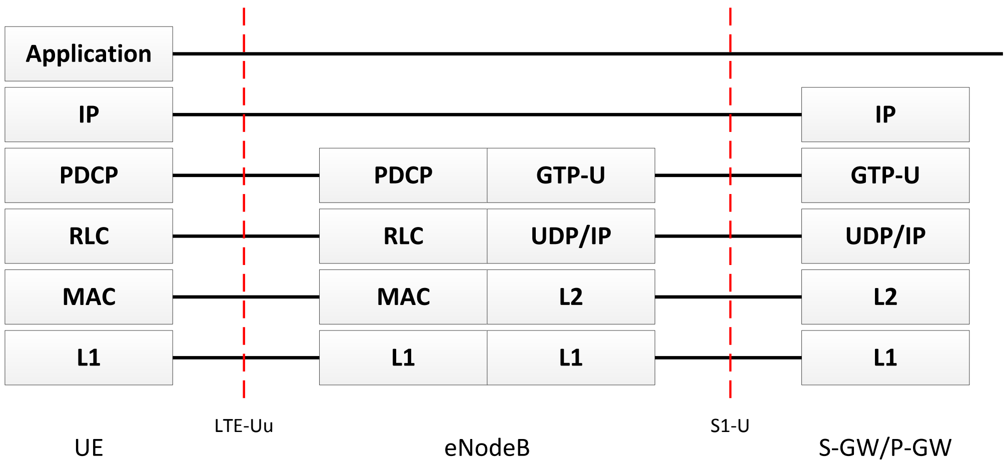


Figure 6: User plane protocol stack for LTE-Uu and S1-U interfaces [6]

The user plane protocol stack of LTE-Uu interface consists of the following protocol layers: Layer 1 (L1), Layer 2 (MAC, RLC and PDCP) and Layer 3 (IP). The structure is identical to the control plane stack apart from the Layer 3, where IP has replaced RRC protocol. L2 and L3 protocols are already described in the control plane part. The application layer carries any desired user data (e.g. FTP or HTTP).

The user plane protocol stack of S1-U interface consists of the following protocol layers: Layer 1 (L1), Layer 2 (L2) and Layer 3 (UDP/IP and GTP-U). The structure is similar to the S1-MME protocol stack. However, the L3 now includes UDP/IP and GTP-U. L1 and L2 protocols are already described in S1-MME part.

UDP/IP (User Datagram Protocol over Internet Protocol) is the transport mechanism used in user plane. UDP is a minimal and unreliable transport protocol that offers no guarantees for the transport, but causes very low header overhead. The congestion control is assumed to be handled in higher layers. UDP/IP is used for routing only inside EPC. [24]

GTP-U (GPRS Tunneling Protocol User Plane) is a tunneling protocol to carry user plane data within EPS. It includes information on Quality of Service (QoS) and UE mobility. [25]

2.5 Channel Structure

Due to shared (common) channel design choice, there are no dedicated channels in LTE. Transport channels are an interface between physical layer and MAC layer. Physical layer channels carry the corresponding transport channel information. Physical layer has to be capable of providing dynamic resource allocation in two ways: data rate variance and resource division between different users.

The channel mapping between logical, transport and physical channels are portrayed in Figure 7 for the downlink and in Figure 8 for the uplink.

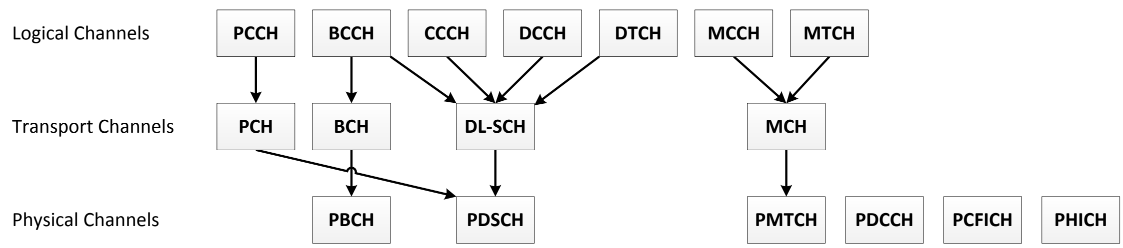


Figure 7: Channel mapping in downlink [7]

2.5.1 Physical Channels

Physical channels transmit the data between nodes. The physical channels have their predetermined mappings on physical resources. Each cell has different mapping based on Physical Cell Identifier (PCI). More information on LTE physical layers and their mapping on physical resources can be found from 3GPP specifications [13].

Physical Broadcast Channel (PBCH) transmits the Master Information Block (MIB) in downlink, which indicates the channel bandwidth and necessary PHICH information. [12] The coded BCH transport block is mapped to four subframes to ensure correct transmission.

Physical Control Format Indicator Channel (PCFICH) is used to inform UE and the network about the number of OFDM symbols used for the PDCCHs. It is transmitted within first OFDMA symbol of each subframe.

Physical Downlink Control Channel (PDCCH) informs UE and the network about the resource allocation of PCH and DL-SCH, and HARQ information. It also carries the uplink scheduling grant.

Enhanced Physical Downlink Control Channel (EPDCCH) is used to inform UE about the resource allocation in DL-SCH, and HARQ information related to DL-SCH.

Physical Hybrid ARQ Indicator Channel (PHICH) carries HARQ ACKs and NACKs in response to uplink transmissions.

Physical Downlink Shared Channel (PDSCH) is the primary channel for transmitting user downlink data. It also carries broadcasting and paging information. [12]

Physical Multicast Channel (PMCH) is similar to the PDSCH and is used to carry multicast user data.

Physical Uplink Control Channel (PUCCH) carries uplink control information if there is no user data transmission. It carries HARQ ACK/NACKs in response to downlink transmission, Scheduling Requests (SR) and Channel State Information (CSI) reports.

Physical Uplink Shared Channel (PUSCH) is used to carry uplink user data and also control information is multiplexed with the user data. [12]

Physical Random Access Channel (PRACH) is used for random access procedure.

Relay Physical Downlink Control Channel (R-PDCCH) informs the network about the resource allocation of DL-SCH, and HARQ information related to DL-SCH. [7]

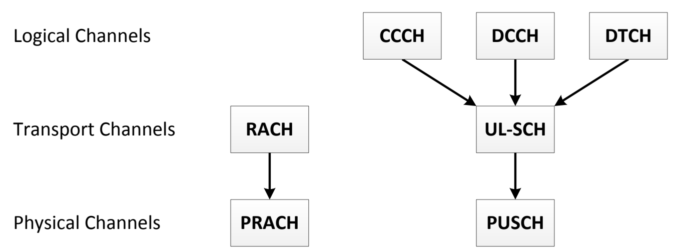


Figure 8: Channel mapping in uplink [7]

2.5.2 Transport Channels

Transport channels are used to carry L2 and L3 information. MAC layer is connected to the physical layer (L1) via transport channels. [4]

Broadcast Channel (BCH) is a downlink channel to broadcast requisite system parameters to enable UE to access the system. The parameters include bandwidth, number of transmit antenna ports and frame number among others.

Downlink Shared Channel (DL-SCH) is used to carry downlink user data for point-to-point connections. User data and higher layer control information in RRC_CONNECTED state is transmitted through DL-SCH.

Paging Channel (PCH) is used to carry paging information in downlink to set the UE from RRC_IDLE state to RRC_CONNECTED state.

Multicast Channel (MCH) is used to transfer multicast content to UEs in downlink.

Uplink Shared Channel (UL-SCH) is a common channel to carry user data and UE originated control information in uplink direction in RRC_CONNECTED state.

Random Access Channel (RACH) is used in uplink to respond to the paging message or to initiate change from idle to connected state, and thus enable UL-SCH transmission. [4] The different UE states are explained in Section 2.6.

2.5.3 Logical Channels

MAC layer service to the RLC layer is conducted through logical channels. Different logical channels are designated for different data transfer services, both for uplink and downlink direction. The logical channels are mapped to the corresponding transport channels. Uplink logical channels are mapped to Uplink Shared Channel (UL-SCH). Random Access Channel (RACH) has no logical channel mapping. [4]

Each logical channel is defined by the type of information that is transmitted [7].

The following logical control channels are defined for LTE:

Common Control Channel (CCCH) is used for transmitting control information between UE and the network. It is used in RRC_IDLE state and it exists in both uplink and downlink.

Dedicated Control Channel (DCCH) is a point-to-point bi-directional channel for transmitting dedicated control information between UE and the network. It is used in RRC_CONNECTED state.

Multicast Control Channel (MCCH) is a point-to-multipoint downlink for controlling multipoint data transfer in MTCH.

Broadcast Control Channel (BCCH) is a downlink channel for broadcasting system control information. It provides necessary information for new UE to access the system.

Paging Control Channel (PCCH) is a downlink channel for paging information and system information change notifications. It is used for paging when the network is unaware of UE's location. [7]

Logical traffic channels:

Dedicated Traffic Channel (DTCH) is a point-to-point, dedicated traffic channel for one UE to transfer user data. It is used both in uplink and downlink.

Multicast Traffic Channel (MTCH) is a point-to-multipoint, dedicated traffic channel from eNodeB to several multipoint users. It is used in downlink direction. [7]

2.6 Mobility

Mobility allows user to move anywhere within the network coverage area while maintaining ability to use voice and data services. This section presents the basic principles of mobility in LTE. Only the intra-LTE mobility is considered in this study. Inter-RAT handovers are thoroughly discussed in e.g. [4].

LTE mobility consists of two procedures: idle state and connected state mobility. In idle state, UE has no active signalling connection towards the network. The UE reports its location on Tracking Area (TA) level, which consists of few hundred cells. In RRC_IDLE state, UE association to the serving cell is called camping. UE measures the signal strength of the cell it is camping and of the neighboring cells. UE performs autonomous *cell reselections* based on the parameters provided by E-UTRAN if needed. However, if the serving cell is strong enough, the UE can stop measuring neighbor cells to save power. Network sets the thresholds and time windows for cell, bandwidth and system changes. In LTE, network controls the transition between RRC_IDLE state and RRC_CONNECTED state and handovers between cells. [4]

RRC_CONNECTED state mobility consists only of *handovers*. The handovers are network controlled and E-UTRAN decides when and where to perform the handover. Intra-LTE handovers are proceeded via X2 interface between eNodeBs. They are based on measurements reported by UE. The parameters for measurements are defined by E-UTRAN. Handovers are targeted to be lossless by using packet forwarding between source and target eNodeB. The signalling is handled directly between eNodeBs. Assuming that MME and S-GW remain unchanged, the EPC has no control over the handovers and the S1 connection is updated only after successful handover (late path switching). The late path switching is performed between eNodeBs and EPC, while the handover is already completed from the UE perspective. [4] [7] The handover procedure is illustrated in Figure 9.

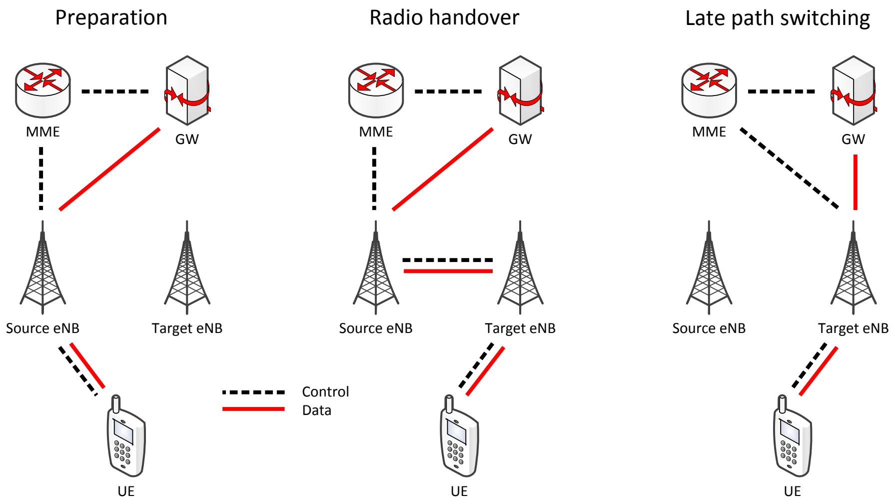


Figure 9: Intra-LTE handover procedure [4]

Intra-LTE handover signalling is visualized in Figure 10. The procedure (including secondary cell addition in Carrier Aggregation) is further explained in Section 5.4.3 using live network RRC message trace from UE.

The radio network measurements specified in LTE for the UE are the following [4]:

Reference Signal Received Power (RSRP) measures the average power of the resource elements containing cell-specific reference signals. RSRP indicates the signal strength and has reporting range of -140 dBm to -44 dBm, with 1 dB resolution [26].

Reference Signal Received Quality (RSRQ) is the ratio of RSRP and RSSI to the reference signals. RSRQ indicates the signal quality and has reporting range of -19.5 dB to -3 dB, with 0.5 dB resolution [26].

Received Signal Strength Indicator (RSSI) indicates the total received wideband power on a given frequency. It includes all received power, and therefore interference and noise as well. It is used for calculating RSRQ, not reported individually.

Channel feedback reporting procedure provides the eNodeB information about the UEs downlink channel state. UE estimates the channel state from the reference symbols in downlink transmissions and then reports the Channel State Information (CSI) using either PUCCH or PUSCH. The feedback reports contain information of scheduling and link adaptation parameters that the UE supports in data reception. The eNodeB scheduler then optimizes the frequency resources using the gathered information. In LTE, the network controls the channel feedback reporting and downlink scheduling. The corresponding uplink procedure is referred as channel sounding, which utilizes Sounding Reference Signals (SRS).

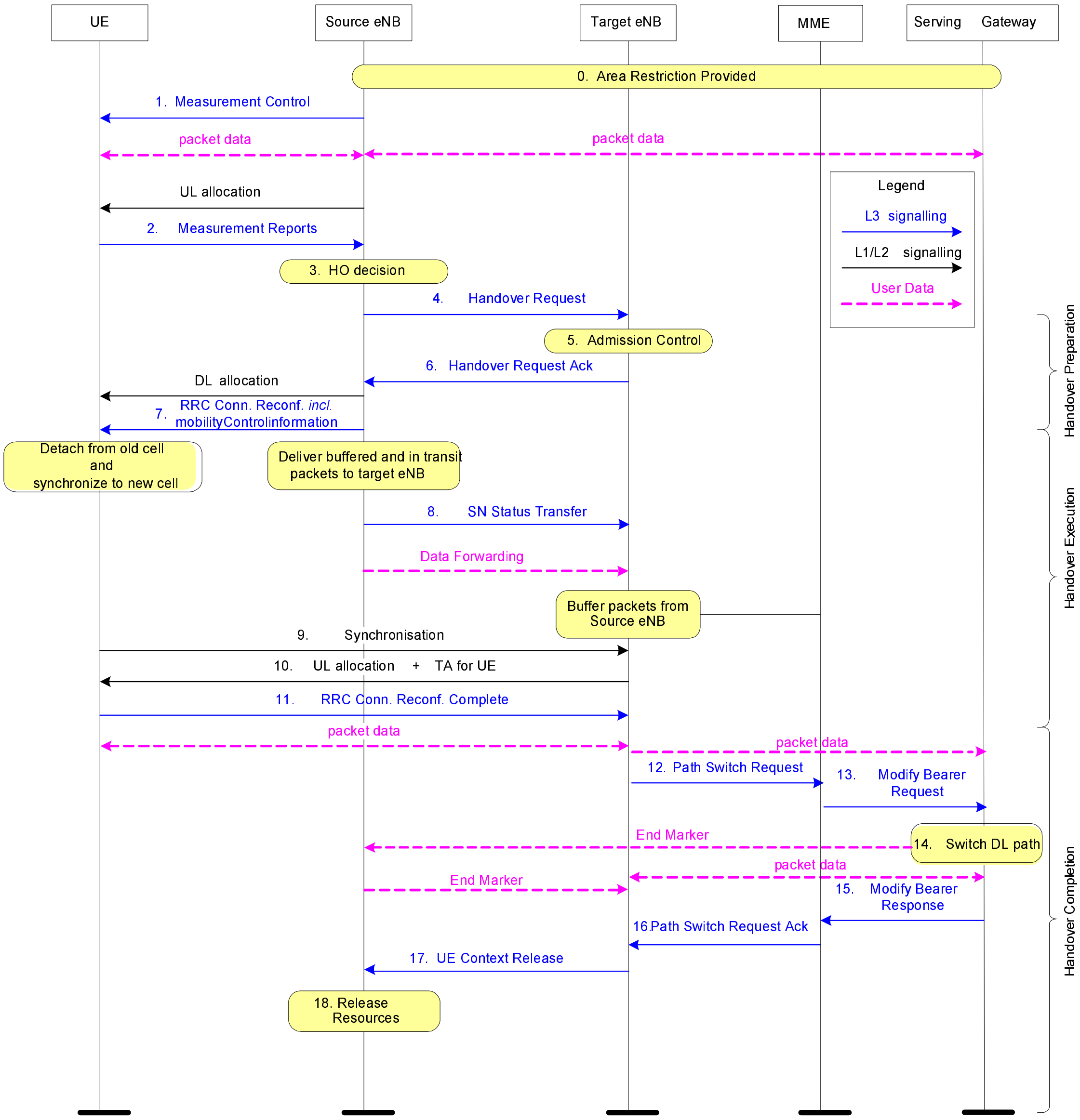


Figure 10: Intra-LTE handover message flow [7]

In LTE the Channel State Information includes the following indicators:

– Channel Quality Indicator (CQI)

– Rank Indicator (RI)

– Precoding Matrix Indicator (PMI)

The most important indicator out of the three is CQI. It provides the eNodeB information on link adaptation capabilities of the UE. CQI is defined as a table of 16 entries with modulation and coding schemes. The CQI table can be further studied from [15]. The UE reports the highest CQI index corresponding to the Modulation and Coding Scheme (MCS) and Transport Block Size (TBS) for which the estimated downlink Block Error Rate (BLER) does not exceed 10 %. CQI value determines the MCS to be used, which in turn determines the modulation (QPSK, 16QAM or 64QAM) and TBS. That effectively defines the possible bit rate for transmission.

RI is the UE initiated recommendation for the number of streams to be used in spatial multiplexing. RI is reported only when operating in MIMO with spatial multiplexing. In the case of single antenna transmission or TX diversity RI is not reported. The RI value typically varies less than CQI and therefore it is reported less often. It is associated with one or more CQI reports and CQI is calculated assuming the particular RI value.

PMI provides preferred precoding matrix in codebook based precoding. PMI is also relevant only with MIMO operation and specifically Closed Loop MIMO. The number of precoding matrices depends on the number of eNodeB antenna ports. [4]

In E-UTRAN, intra-frequency neighbour relations can be added automatically with Automatic Neighbour Relations (ANR). When UE moves towards new cell, it identifies the Physical Cell Identity (PCI) of the new cell from synchronization signals. If the handover threshold is exceeded, UE sends measurement report to the serving eNodeB. If the target cell is not neighbour to the serving cell, there is no X2 connection between the eNodeBs. PCIs are not unique in the E-UTRAN, and therefore they are not sufficient for establishing new X2 connection. Therefore, UE interprets the global cell identity from BCH of the target cell. Using the global cell ID, serving eNodeB can track the transport layer address of the target eNodeB and establish the X2 connection. Cell change can then be performed according to the handover procedure. [4]

3 LTE-Advanced

3GPP LTE-Advanced can be considered as a toolbox that provides advanced features on top of existing LTE Release 8. The features can be implemented separately to the network. Such features are Carrier Aggregation, Heterogeneous Networks, Relay Nodes and Coordinated Multipoint transmission. LTE-Advanced includes also improvements to multi-antenna schemes and to Self-Organizing Networks. [5] This thesis focuses primarily on Carrier Aggregation, which is covered in Section 4. This section presents the IMT-Advanced requirements (Section 3.1) for advanced radio access technology and gives overview of few other LTE-A features in Section 3.2.

3.1 IMT-Advanced Requirements

The International Telecommunication Union Radiocommunication Sector (ITU-R) initiated a process to create a framework for new International Mobile Telecommunications Advanced (IMT-Advanced) system in 2008. ITU-R requested for proposals that would fulfill the requirements for new radio system. 3GPP responded to this request by submitting the LTE-Advanced proposal in 2009. [5]

ITU-R defined the following requirements: the IMT-Advanced capabilities should go beyond the capabilities of IMT-2000. IMT-Advanced system has to support low and high mobility with wide range of data rates in multiple user environments. [27]

The key requirements of IMT-Advanced:

- High degree of worldwide functionality, while retaining the flexibility to support wide range of services and applications in a cost efficient manner
- Compatibility with IMT and fixed network services
- Capability of interworking with other radio access systems
- High quality mobile services
- User Equipment (UE) suitable for worldwide use
- User-friendly applications, services and equipment
- Worldwide roaming capability
- Enhanced peak data rates to support advanced services and applications
    - 100 Mbit/s for high mobility
    - 1 Gbit/s for low mobility

IMT-Advanced also included requirements for spectral efficiency, latency, mobility and handover delay. The spectral efficiency is measured in bit/s/Hz/cell. In other words, it is the cell throughput divided by the bandwidth. The peak spectral efficiency is the highest theoretical data rate (divided by bandwidth) when all radio resources are assigned to single user. The minimum requirement for downlink peak spectral efficiency is 15 bit/s/Hz. The minimum requirement for uplink is 6.75

bit/s/Hz. The values were defined assuming antenna configurations 4×4 (DL) and 2×4 (UL).

According the requirements, control plane latency should be less than 100 ms. This includes transition between different connection states (e.g. from idle state to connected state). The downlink paging delay and wireline network signalling delays are excluded. The user plane latency is defined in the connected state as a time between an SDU packet being available at the IP layer of the transmitter and the availability of PDU packet at IP layer of the receiver. User plane latency should be less than 10 ms in unloaded conditions.

The following mobility scenarios should be supported: stationary (0 km/h), pedestrian (0 to 10 km/h), vehicular (10 to 120 km/h) and high speed vehicular (120 to 350 km/h). The handover interruption time is defined as the time during which UE cannot exchange user plane packets with any eNodeB. The requirement for data interruption in intra-frequency handover is 27.5 ms and in inter-frequency handover 60 ms. [27]

3.2 LTE-Advanced Solutions

The 3rd Generation Partnership Project (3GPP) attempted to meet the IMT-Advanced requirements with LTE-Advanced specification. The specification is partially more evolved than the IMT-Advanced requirements. It was seen that just fulfilling the IMT-Advanced requirements there would have been only minor leap forward from LTE Release 8 specification. The 3GPP decided to set higher design goals. The most significant differences are in spectral efficiency requirements. [5]

The following areas were studied as part of the LTE-Advanced study phase:

- Capacity and cell edge performance (data and VoIP)
- Latency for control and user planes
- Handover performance
- Peak spectral efficiency (and peak data rates)
- Radio Frequency (RF) aspects

The 3GPP study results showed that the technology components that were considered for LTE-Advanced could achieve or exceed the requirements. The actual specification phase followed after the study phase had been completed. The Release 10 specifications were completed in June 2011. The LTE-A technology components were added in Release 10, which also contains Release 8 and 9 LTE features. [5]

The Carrier Aggregation (CA) band combinations are release independent and each combination is defined as separate work item. The band combinations are implemented on top of Release 10, assuming they do not require any Release 11 specific features. In principle, new band combination or frequency band can be added to 3GPP specification without having to wait for ongoing release to be completed as long as band specific RF and performance requirements are achieved. [5]

Along with Carrier Aggregation, the LTE-A employs few other features: support for Coordinated Multipoint (CoMP), Heterogeneous Networks (HetNet) and Relay Nodes. LTE-A also introduces enhancements to MIMO. These technologies are described in the following sections.

3.2.1 Coordinated Multipoint

Advanced interference avoidance systems have become increasingly interesting within the telecommunication industry. Coordinated Multiple Point transmission and reception (CoMP) was added as a work item to 3GPP LTE-Advanced framework in 2011. It is one of the core features in Release 11. CoMP provides the necessary specification for cooperative transmission and reception. It aims to mitigate the interference and to use coordination of multiple transmission and reception sources in such way that the cell throughput can be improved.

In practical networks, CoMP is likely to be deployed first into a single macro base station. Thus, it would have an advantage of not needing any inter-eNodeB connections. CoMP requires fast signalling between cells to operate properly. In the future, inter-eNodeB CoMP could be also realized. CoMP can also be implemented in heterogeneous networks. First option is to use pico cells as independent eNodeBs that communicate with macro eNodeB and the second option is to use Remote Radio Heads (RRH) that are controlled by the macro eNodeB system module. [28]

In downlink there are two possible methods. In Coordinated Scheduling and Beamforming (CS/CB), UE receives data from the serving cell. Meanwhile, the adjacent cells of a CoMP set dynamically coordinate their transmissions to other UEs in such way that inter-cell interference is avoided. A CoMP set is a group of cells from which UE can receive data. The functionality is similar to the WCDMA active set. CS/CB can be considered as enhancement to Release 8 Inter-cell Interference Coordination (ICIC). Joint Transmission (JT) is namely a techique, where CoMP set cells jointly transmit to one or multiple UEs. Each cell in the CoMP set has to be aware of channel conditions of each UE, to be able to optimize the transmission. Therefore, JT requires fast coordination and backhaul connectivity between the cells. The reference signal structure was redesigned in Release 10. The common reference signals for CSI and user specific reference signals for decoding were separated. That enables UE specific beamforming in the downlink. [5]

Uplink coordinated reception utilizes the previously interfering signal as an advantageous signal and decodes it accordingly. [28] Uplink CoMP is simple from the specification point of view. It can be used for Release 8 UEs as it does not require changes to the UE transmission. In UL CoMP, the signal from the UE is received by several antennas, which are then forwarded to central receiver for combining. [5]

In earlier releases of LTE, UE had only one cell as a uplink reception point. The UEs were separated with orthogonal codes. CoMP requires different approach to identifying different UEs, since the uplink signal could be desired signal also in another cell. Release 11 introduced a new capability for configuring reference signal parameters. The initialization of the pseudo-random sequences for identifying UEs is no longer associated with PCI. Instead, a so-called Virtual Cell Identity (VCID) is used to determine correct UE. This enables UE to be served by another cell in the uplink transmission. [28]

Uplink CoMP reception improves the performance in two ways. Firstly, the signal quality is improved by collecting more signal energy at the eNodeB and by increasing receiver antenna diversity. Secondly, the coordinated reception can significantly improve the inter-cell interference cancellation. The best gains can be achieved at cell edge where two cells transmit using similar power. In intra-eNodeB CoMP, the location where two cells transmit using similar power is at the intersection of two sectors. CoMP can provide more homogenous quality of service across the network coverage area.

CoMP requires fast backhaul transmission and additional computing power. Downlink CoMP does not provide substantial gains, but it is relatively simple to implement in the network. That is when using intra-eNodeB CoMP between multiple sectors. However, downlink CoMP requires Release 11 supporting UEs. In the uplink, the gains are better. The simulations have shown that cell edge data rates can increase by 40–50 %. In the heterogeneous networks the gains can be even higher. Uplink CoMP can be implemented using existing Release 8 capable UEs. [5]

3.2.2 Heterogeneous Networks

The rapidly growing data traffic will overwhelm the macro cell capacity in the near future. Even if more spectrum and more advanced features are implemented there will be need for small cell deployment within the macro layer coverage. Increasing the number of base stations is the most straightforward way to increase the network capacity. In more dense locations low-power nodes are sufficient for providing additional capacity. The small base stations are advanced in hardware point of view and the intelligent Self Optimizing Network (SON) algorithms reduce the amount of configuration operations. [5]

The co-existence of macro and small cells, and also different radio access technologies create more layers and diversity into network. This kind of network is referred as a Heterogeneous Network (HetNet). [29] They are a pragmatic and inexpensive way to increase LTE network capacity. Macro cells provide broad coverage and low-power nodes can be deployed in densely populated locations. Micro cells are smaller scale outdoor cells, used in urban areas. They often utilize the same radio equipment as macro cells. Micro cells are typically deployed with lower gain antennas and may use higher frequency bands than macro cells. Both macro and micro cells require fixed backhaul (e.g. fiber) connection. [5]

Pico cells are eNodeBs that have low transmit power compared to macro cells. The transmit power is typically less than 2 W. They are typically deployed as hotspots with omnidirectional antennas. Pico cells can utilize X2 interface based Inter-cell Interference Coordination (ICIC). Pico cells use similar wired backhaul as macro eNodeBs. [29]

Femto cells are typically user deployed network nodes for improving indoor capacity and coverage. The backhaul is facilitated with e.g. DSL or cable modem connection. The transmit power is typically 100 mW or less. Femto cells can be either open or closed from the public. Open femto cells are basically pico cells with other than operator provided backhaul. Closed femto cells restrict the access to predefined Closed Subscriber Groups (CSG). Closed femtos create interference to UEs outside of CSG and hence coverage holes to the network. [29]

Relay nodes are other possible solution to be used in heterogeneous networks. Relay nodes are covered in Section 3.2.3. A model of HetNet layout is presented in Figure 11.

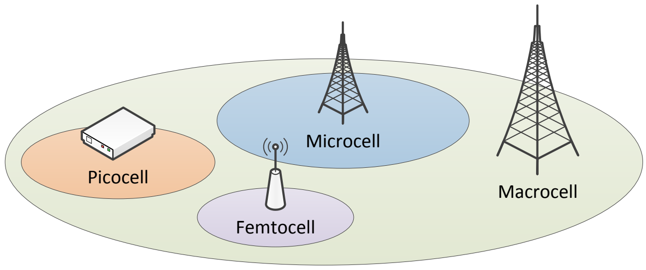


Figure 11: Heterogeneous network layout [29]

Heterogeneous Networks consist of high-power macro cells and low-power small cells. There can also be a mixture of open and closed subscriber access. HetNets have significant power disparities, which are disadvantageous to the small cells. One solution is to deploy small cells on a different frequency than macro network. If each network layer uses its own carrier frequency, there are no interference or coverage problems. However, that typically leads to inefficient use of the spectrum. This is one scenario where Carrier Aggregation increases the system efficiency as UE can utilize the capacity of both carriers. [29]

Another deployment scenario for HetNets is referred as co-channel deployment. All network nodes are deployed on the same carrier frequency to avoid segmentation, need for large amount of spectrum or Carrier Aggregation. [29] The UEs connect to the strongest cell by default. Assumingly the macro cells use significantly larger transmission power than small cells. Therefore, the cell border is closer to the small cell. However, the uplink Tx power is the same towards both macro and small cell. The cell edge in uplink point of view is in the middle of these two nodes. Either the UE will cause uplink interference to the small cell or if the UE is connected to the small cell the macro cell will cause significant downlink interference. Severe interference affects also to the control channel and may block the UE connectivity to the base station. [5]

Obviously, the interference should be controlled and reduced. One ICIC method is to use adaptive resource partitioning, where eNodeBs negotiate their resource allocation through X2 interface. A macro cell might inform nearby small cells which part of the resources it has allocated for transmission and which subframes are *almost blank*. As the small cells are aware of the interference pattern of the macro cell, they can utilize the almost blank subframes for their transmission. Also, advanced interference cancellation receivers could be implemented at UE. [29]

Self-Organizing Networks (SON) has been part of the LTE Release 8 specification. The motivation for SON is to maximize the automation of network configuration and optimization, and to minimize the human intervention. The principal objective is cost reduction by reducing human involvement in network operation. In 3GPP Releases 8 and 9, SON related tasks included interference control, coverage optimization, mobility load balancing, mobility robustness optimization and energy saving management. Releases 10 and 11 extend SON to cover heterogeneous networks. SON is a critical technology in order to utilize the full potential of heterogeneous networks. [30]

Self-configuration is a process where newly deployed cells are automatically configured during installation. For instance, Physical Cell Identity (PCI) and radio resource self-configuration schemes are required. Also, self-optimization processes are needed in existing cells as the network evolves. The neighbor relations and load balancing are two of the most important optimization areas.

Working SON configurations considering PCI assignment and radio resource management have already been proposed. Automated inter-RAT neighbor relations, load balancing and capacity management require more research. Self-detection of outages and self-healing of small cells in a heterogeneous network are also part of the future work. [30]

3.2.3 Relay Nodes

LTE-Advanced typically operates on high frequencies, which suffer from severe radio propagation losses, especially inside buildings. The coverage problems can be solved with increasing eNodeB density. Deploying more macro eNodeBs is, however, expensive and not even feasible in certain locations. [31] Traditional solution for indoor coverage has been RF repeaters, which amplify the desired signal, but also the interference. Furthermore, repeaters do not provide any encoding or decoding functionality.

Relay nodes utilize the LTE Uu interface for UE to relay connection, specified in Release 8. In Release 10, the new Un interface was specified for backhaul connection to the donor eNodeB. Thus, relay node utilizes wireless backhaul connection. From the network point of view, relay appears as an additional sector in the eNodeB. The donor eNodeB acts as a proxy for the S1 and X2 interfaces and forwards signalling towards core network and other eNodeBs. [5] The relay node operation is presented in Figure 12.

Relay nodes are small nodes with low power consumption, which offers flexibility in deployment and installation. It also removes the need for fixed backhaul connection. [31] Relay backhaul can operate either within the same band as LTE Uu interface (inband) or on a different band (outband). In the case of inband backhaul, the access link and the backhaul are separated in time domain (TDD) to avoid interference.

Relay nodes decode the packets received from donor eNodeB and transmit only important packets to the UE. The interference is not amplified. Relays also utilize

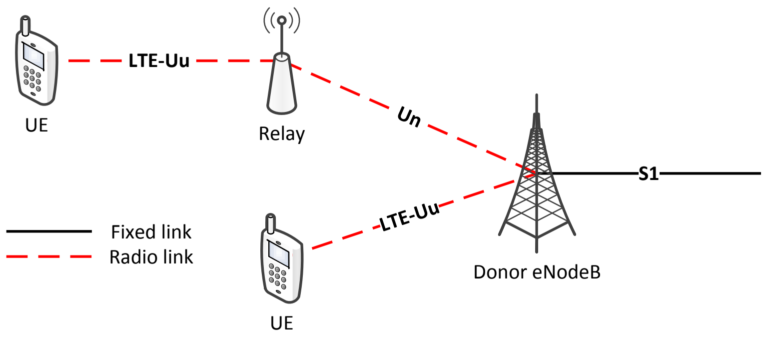


Figure 12: Relay node and donor eNodeB [5]

optimized packet scheduling. The transmission data rate over the Un interface can be higher than over the Uu interface towards the UE. Relays typically provide improved SNR conditions to the UE when compared to RF repeater. [5]

When deployed at the cell edge, relays improve both coverage and capacity. At cell edge they can be as efficient as pico cells, while they do not need wired backhaul. The feasibility of relay node deployment scenarios has been proven in simulation studies, when the objective has been to improve coverage. Pico cells typically provide better throughput performance. [31]

Relays are compatible with Release 8 UEs and they appear as a normal eNodeB to the UE. Relay node handles encoding, decoding and packet scheduling operations similarly to the eNodeB. In the future, 3GPP will specify mobile relay solutions that could be used in high-speed vehicles such as trains. Another future development could be using multiple radio access technologies at the Uu interface, while retaining only LTE in the backhaul. [5]

3.2.4 MIMO Enhancements

Downlink MIMO (Multiple Input Multiple Output) was already introduced in LTE Release 8 specification. Release 10 adds few improvements on top of existing specification. The principal design criteria for the enhancements was to maintain backward compatibility towards earlier releases. Other design points were to reduce signalling overhead and to support up to eight-antenna transmission.

Downlink MIMO features:

– Support for eight antennas and parallel data streams (8×8 MIMO).

– New reference signal solutions and improved feedback from the new Transmission Mode 9 (TM9) are needed in the case of 8×8 MIMO.

– Transmission with two, four or eight antennas. Channel State Information Reference Signals (CSI-RS) are used to obtain Precoding Matrix Indication (PMI) feedback.

– UE specific demodulation Reference Signal (URS) can be transmitted within the same PRBs as the data in MIMO transmission.

– MIMO feedback is optimized for both single-user and multi-user scenarios. [5]

Downlink MIMO is a physical layer function. However, the scheduler at MAC layer decides the type of connection based on CQI feedback. Scheduler decides which MIMO rank should be used and whether multi-user MIMO (MU-MIMO) operation could be utilized. CSI-RS provides the feedback to the UE. The scheduler considers the received feedback, pre-defined user priorities, buffer status and possibly other vendor specific criteria in its decisions. If Carrier Aggregation is used, UE could receive resources from several carriers and also the use of MIMO is decided separately for each carrier. The use of downlink MIMO improves the peak data rates with addition of several parallel data streams. Data rates are further discussed in Section 4.6.2.

In order to fulfill the IMT-Advanced requirements for uplink transmission, 3GPP introduced MIMO for uplink in Release 10. Also the uplink MIMO maintains backward compatibility with earlier LTE releases. [5]

The benefits of uplink MIMO:

– Uplink peak data rates are increased (Section 4.6.2)

– Uplink cell capacity increased depending on the number of antennas (up to 4×4 MIMO)

– Multi-user MIMO improves the flexibility when pairing the users

As the case was with downlink MIMO, uplink MIMO mostly impacts to the physical layer, but also to the MAC layer. The uplink scheduler considers whether UE is MIMO capable or if the virtual MU-MIMO is needed. The scheduler needs to decide which users can be paired together. In MU-MIMO, two UEs can be allocated to use same uplink frequency resources on different MIMO layers. The Orthogonal Cover Codes (OCC) are used to identify users in frequency domain. Uplink MIMO requires the use of two or more power amplifiers and transmit antennas at the UE. The implementation is rather difficult within the limits of available transmission power. UE power consumption can be reduced by turning off some antennas when there is less uplink transmission. [5]

4 Carrier Aggregation

The key requirements for the 3GPP LTE-Advanced were spectrum flexibility and spectrum compatibility. Spectrum flexibility refers to the possibility to operate on non-contiguous spectrum and spectrum compatibility is needed for backward compatibility with Release 8 LTE. [32] The most important technology component in LTE-A is the Carrier Aggregation (CA) [33].

This section provides a detailed description on Carrier Aggregation. The principles and possible deployment scenarios are presented in Sections 4.1 and 4.2. The impact on radio protocol level for both downlink and uplink is discussed in Section 4.3. The Section 4.4 covers the radio resource management and the changes in mobility management in CA are then presented in Section 4.5. Furthermore, the CA performance requirements and UE capabilities are described in Section 4.6. The possible band combinations for CA are discussed and listed in Section 4.7. Finally, the future development of Carrier Aggregation and LTE-Advanced in general is discussed in Section 4.8.

4.1 Overview of Carrier Aggregation

The maximum carrier bandwidth in LTE is 20 MHz. Wider bandwidth is required to reach higher data rates. However, such spectrum is rarely available for an operator. Furthermore, if wider than 20 MHz bandwidth has to be allocated for several operators, the set of possible frequencies is very limited. Wider than 20 MHz bandwidth would also be incompatible with Release 8 capable UEs.

3GPP Release 10 introduced a new LTE-Advanced technology referred as Carrier Aggregation, which supports the use of multiple LTE carriers for wider bandwidth transmission. Up to five Component Carriers (CC) and maximum of 100 MHz of spectrum can be aggregated, depending on the UE and eNodeB capabilities. CA provides increased data rates for the users and allows operators to fully utilize fragmented LTE spectrum. In CA, the resources of two or more LTE carriers can be allocated for single UE. CA is backward compatible with earlier LTE Releases. Release 8 capable UE uses one LTE carrier, as the Release 10 capable UE can utilize multiple carriers. [5]

CA required changes also to the UE functionality and they were introduced in Release 10. Downlink and uplink control plane design was modified, and receiver chains were upgraded to support more efficient data transmission. [34]

In principle, it is possible to configure different number of UL and DL carriers, from different carriers for the UE. However, CA has few practical limitations. The number of CCs depends on the UE capabilities and there cannot be more UL CCs than DL CCs. Component carrier is a Release 8 carrier and therefore it can have bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. The spacing between center frequencies of contiguous carriers is $N \times 300$ kHz. [7]

4.2 Deployment Scenarios

CA provides a good business opportunity to operators by allowing them to turn their investments in frequency licenses into improved data rates in the radio access network. In addition, CA simplifies the multi-band traffic management through load balancing between different carriers. There are three different methods for implementing CA. [5] They are presented in the following list and in Figure 13.

Intra-band contiguous transmission on adjacent carriers. Typically, there is no paired spectrum allocated to one operator from adjacent carriers. Intra-band CA is easy to implement in UE since the same power amplifier can be used.

Intra-band non-contiguous transmission on same band but non-adjacent carriers. This method is possible if an operator has at least two carriers within the same band. It is, however, more complex to implement in the UE.

Inter-band non-contiguous transmission on two or more separate frequency bands. This is the most typical use case for CA. However, it requires multiple transceivers in the UE, which increases cost and power consumption. [5]

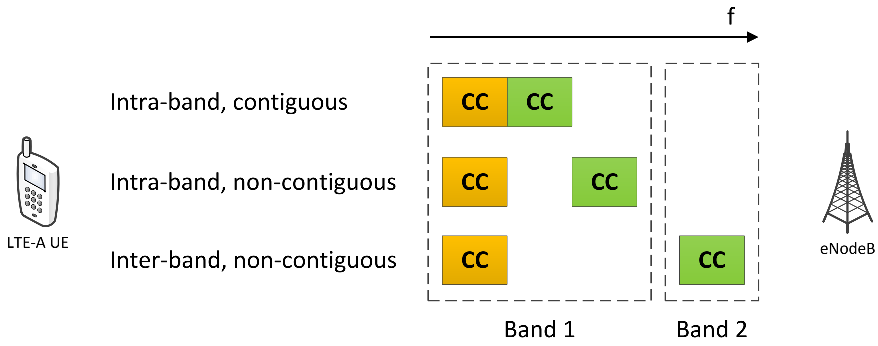


Figure 13: Intra-band and inter-band Carrier Aggregation operation

The possible CA deployment scenarios are presented in Figure 14. There are two frequencies, of which the frequency F1 represents the macro layer. Frequency F2 is deployed in five different ways. The first two scenarios are the most typical choises for CA deployment in a macro network. The difference is that the former scenario represents the intra-band solution and latter represents the inter-band solution, where frequency F2 is the higher frequency. The third scenario offers more homogeneous performance over the entire coverage area. The fourth scenario utilizes Remote Radio Heads (RRH), which offer the additional capacity in hotspots. Repeaters or relays are used in the fifth scenario to extend the higher frequency coverage. [7]

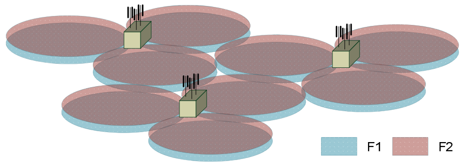
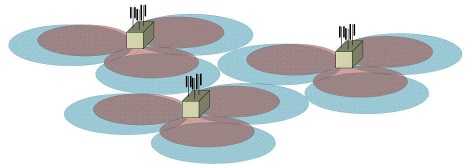
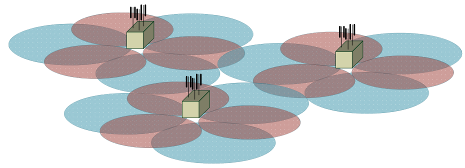
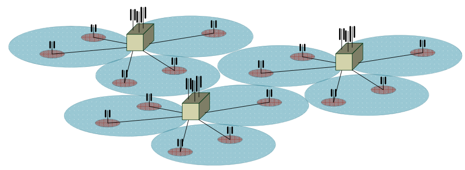
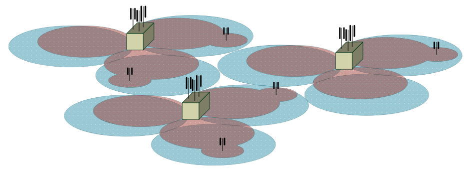
#	Description	Example
1	F1 and F2 cells are co-located and overlaid, providing nearly the same coverage. Both layers provide sufficient coverage and mobility can be supported on both layers. Likely scenario is when F1 and F2 are of the same band, e.g., 2 GHz, 800 MHz, etc. It is expected that aggregation is possible between overlaid F1 and F2 cells.	
2	F1 and F2 cells are co-located and overlaid, but F2 has smaller coverage due to larger path loss. Only F1 provides sufficient coverage and F2 is used to improve throughput. Mobility is performed based on F1 coverage. Likely scenario when F1 and F2 are of different bands, e.g., F1 = {800 MHz, 2 GHz} and F2 = {3.5 GHz}, etc. It is expected that aggregation is possible between overlaid F1 and F2 cells.	
3	F1 and F2 cells are co-located but F2 antennas are directed to the cell boundaries of F1 so that cell edge throughput is increased. F1 provides sufficient coverage but F2 potentially has holes, e.g., due to larger path loss. Mobility is based on F1 coverage. Likely scenario is when F1 and F2 are of different bands, e.g., F1 = {800 MHz, 2 GHz} and F2 = {3.5 GHz}, etc. It is expected that F1 and F2 cells of the same eNB can be aggregated where coverage overlaps.	
4	F1 provides macro coverage and on F2 Remote Radio Heads (RRHs) are used to improve throughput at hot spots. Mobility is performed based on F1 coverage. Likely scenarios are both when F1 and F2 are DL non-contiguous carrier on the same band, e.g., 1.7 GHz, etc. and F1 and F2 are of different bands, e.g., F1 = {800 MHz, 2 GHz} and F2 = {3.5 GHz}, etc. It is expected that F2 RRHs cells can be aggregated with the underlying F1 macro cells.	
5	Similar to scenario #2, but frequency selective repeaters are deployed so that coverage is extended for one of the carrier frequencies. It is expected that F1 and F2 cells of the same eNB can be aggregated where coverage overlaps.	

Figure 14: CA deployment scenarios [7]

4.3 Radio Protocol Impact

Carrier Aggregation operation impacts to the radio protocols that were described in Section 2.4. This section covers the changes from Release 8 specification. As already mentioned, CA uses parallel LTE carriers for transmission. Component carriers are normal Release 8 compatible carriers, which have inherited the transmission schemes (multiple access, modulation, channel coding) from LTE Release 8.

CA utilizes Release 8 user and control plane design to maintain backward compatibility. In Release 10 additional procedures, such as cell management, have been implemented for handling multiple component carriers. The component carrier is often referred as *serving cell* by the higher layer functions. UE has a single serving cell for all required control information (such as RRC connection maintenance), and it is referred as the Primary Cell (PCell). Other serving cells are known as Secondary Cells (SCell). SCells do not handle control plane procedures such as PUCCH configuration, radio link monitoring, RACH procedures or scheduling. [34]

4.3.1 Downlink

Providing Carrier Aggregation capabilities in downlink is entirely a function of the eNodeB. In the user plane, CA is invisible above the Medium Access Control (MAC) layer. The Radio Link Control (RLC) layer provides the logical channels. The operation on the RLC is not different from Release 8. Packet Data Convergence Protocol (PDCP) operations such as ciphering and header compression are performed as in Release 8. RLC and PDCP layers are considered as transmission pipelines, managed by single scheduling component at MAC layer. [5]

The differences compared to Release 8 are on the physical layer (L1) and on the MAC layer. From Release 10 onwards, MAC layer supports controlling up to five component carriers at physical layer. [34] In CA, MAC is used to divide the data into multiple streams, one for each downlink component carrier. The CA impacts to few MAC procedures such as handling multiple PDSCH and PUSCH [32]. MAC layer informs the RLC layer of transmission possibilities on all carriers, and the RLC packet data units are formed accordingly. MAC and RLC functions are co-located in eNodeB. [5]

The key difference between the Layer 2 protocol structure of Release 8 and of Release 10 is that there is a designated Hybrid Automatic Repeat reQuest (HARQ) entity for each component carrier. The actual HARQ operation is the same as in Release 8. A failed transport block needs to be retransmitted on the same carrier using the same HARQ entity. As the HARQ operation is performed for each component carrier, the associated control signalling (e.g. PDCCH, PHICH, PCFICH and SRS) is also defined for each component carrier. Multiplexing the multiple data streams is performed in the MAC layer, but above the HARQ process. [32] The Layer 2 structure is presented in Figure 15.

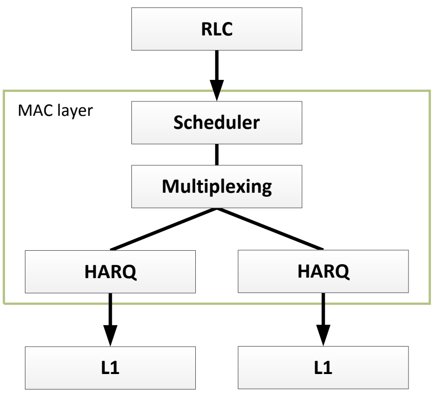


Figure 15: MAC layer and HARQ structure with two component carriers [5]

A CA capable UE has to be capable of processing multiple transport blocks within a TTI. [32] UE has only one active RRC connection regardless of the number of carriers used. PCell is always active and handles transmitting the control information. MAC is responsible for cell management. After the RRC connection has been established, MAC layer can configure SCells, if the UE is CA capable. UE receives the MAC layer Control Element (CE) for each dedicated SCell. SCell activation and deactivation procedures are initiated with CEs. These operations can be used, if the radio conditions change significantly or the amount of data in the buffer increases or decreases.

The process, where RRC connection is established first, followed by MAC layer activation is required to reduce the UE power consumption. If there is no data to transfer, the unnecessary receivers are turned off. Furthermore, the SCells are deactivated, if there is no data in the buffer. UE does not measure or report Channel State Information (CSI), including CQI, from the deactivated cells. [5] The cell management procedures are further discussed in Section 4.5.

4.3.2 Uplink

In principle, the uplink Carrier Aggregation is similar to the downlink CA. Uplink CA specification was introduced in Release 10. It enables UE transmission using two or more carriers instead of one.

Primary differences in uplink compared to Release 8:

- Contiguous spectrum allocation is not necessarily used
- PUCCH is transmitted only on Primary Cell (PCell) frequency.

If the UE or the E-UTRAN supports only downlink CA, PUCCH and PUSCH are transmitted on the PCell frequency. If there is uplink data scheduled on the PCell, the control and data are multiplexed on the PUSCH, as in the Release 8 specification. The Release 10 enables transmitting PUCCH and PUSCH simultaneously. This allows optimizing the power levels of the channels independently. The physical layer takes care of the data retransmissions if needed, but the control information is not retransmitted. Therefore, it is beneficial to use higher transmission power and more robust modulation scheme with the control channel. The discontinuous allocation of resource blocks provides more possibilities for scheduling. [5]

The signalling capabilities on Release 10 already support maximum of five uplink carriers. However, there will be band combinations specified for only two uplink carriers in the first phase of uplink CA implementation. This is due to issues related to the limited UE transmission power, which require solutions. [5] As of early 2015, there are no UL CA capable terminals in the market.

Downlink signalling provides necessary information for scheduling the PUSCH resources. The eNodeB uplink scheduling is based on Sounding Reference Signal (SRS) messages that are sent along with MAC layer buffer status reports for each uplink carrier. The scheduler also has to ensure that the UE has sufficient Tx power to transmit two carriers simultaneously. If not, the uplink connection is downgraded to one LTE carrier. The use of uplink CA is not visible to the UE mobility measurements and the use of uplink CA can continue after the handover, if CA is also supported in target eNodeB. If not, the CA can be disabled using the same *RRCConnectionReconfiguration* message that is used for handover command. [5]

Uplink Control Information (UCI) provides HARQ feedback to PDSCHs, Channel State Information (CSI) and Scheduling Requests (SR). UCI can be transmitted on PUCCH if there are no other transmissions, and otherwise on the PUSCH. Release 10 supports also simultaneous PUSCH and PUCCH transmission in a single subframe. Therefore, the UCI overhead on PUSCH can be avoided by utilizing existing PUCCH resources. PUCCH can only be transmitted in PCell. If possible, UCI is always transmitted on a single PUSCH. [34]

PUCCH format 3 was introduced in Release 10 to support HARQ feedback in downlink CA capable UE. PUCCH format 3 utilizes SC-FDMA waveform with five SC-FDMA symbols per slot carrying HARQ feedback information. Additionally, one or two symbols are used to carry Reference Signals (RS) in order to enable coherent demodulation of feedback signal. An Orthogonal Cover Code (OCC) with length of five bits is applied to the encoded HARQ feedback in respective SC-FDMA symbols. This enables multiplexing the feedback of up to five UEs into one resource block. [34]

Uplink power control is used to determine PUSCH and PUCCH Tx power in order to ensure reliable transmission. The LTE uplink power control consists of an open-loop component adjusting for the path loss between eNodeB and UE, and of a closed-loop component to follow the Transmission Power Control (TPC) commands from PDCCH. The uplink power control process is independent for each activated component carrier. The determined transmission power for PUSCH and PUCCH is referred as nominal transmission power. The difference in power control operation compared to Release 8 occurs, if the sum of nominal transmission powers exceed the limit UE is capable of transmitting. [32]

UE can transmit one PUCCH, one PUSCH with UCI or several PUSCH without UCI in the same subframe. The control information is more important than user data. Therefore, the UE transmission power is distributed based on the following priority: PUCCH, PUSCH with UCI and PUSCH without UCI. The nominal transmission power for higher priority channel is guaranteed first, if the UE maximum total output power is reached. UE reduces the transmission power of PUSCHs without UCI.

The E-UTRAN may be unaware of the UE maximum total transmission power, e.g. in scenario where UE has missed the TPC commands or the UE uses Maximum Power Reduction (MPR) scheme. Therefore, UE sends Power Headroom Reports (PHR) to provide accurate transmission power information to the eNodeB. [34] It is used to estimate the difference between nominal maximum output power and estimated PUSCH transmit power. Using this information eNodeB can perform uplink scheduling with optimal transmission power. In CA, there can be multiple UL component carriers in use and each CC can experience different radio channel conditions. Thus, the power headroom of each carrier should be reported and the power control should be applied on each carrier. [32]

4.4 Radio Resource Management

Radio Resource Management (RRM) is a set of system level functions that control the resource allocation in LTE air interface. The objective for RRM is to maximize the spectral efficiency by restricting the interference and optimizing the resource usage. It also manages the UE mobility. RRM provides means to manage radio resources in single and multi-cell scenarios. [7] The requirements defined for RRM in Release 8 are applicable for LTE-Advanced as well [35].

All the RRM functions are located in the eNodeB:

Radio Bearer Control (RBC) is used for establishing and releasing radio bearers and configuration of radio resources for them. RBC considers the overall resource situation in E-UTRAN and the QoS requirements of radio bearer requests. RBC is also responsible of maintaining the radio bearers during mobility.

Radio Admission Control (RAC) is responsible of admitting or rejecting the new radio bearer requests. RAC optimizes the resource usage by accepting all requests if there are radio resources available and rejecting them if proper QoS cannot be maintained for existing connections.

Connection Mobility Control (CMC) manages the radio resources within idle or connected state mobility. E-UTRAN broadcasts the parameters for UE measurements and mobility thresholds. Mobility of radio connections is supported in handover.

Dynamic Resource Allocation (DRA) or Packet Scheduling (PS) allocates the radio resources for user and control plane packets. It takes QoS requirements of the radio bearers, channel quality information, buffer status and interference situation into account.

Inter-cell Interference Coordination (ICIC) is used to manage the radio resources in such way that inter-cell interference is reduced. It considers the situation over multiple cells.

Load Balancing (LB) handles the traffic distribution over multiple cells. Load balancing algorithms may result to handovers or cell reselections to even the load between high and low load cells. [7]

Carrier Aggregation affects in RRM and overall performance by increasing efficiency in load balancing and resource sharing, and allowing frequency domain joint scheduling. [5]

The scheduling function is located in the MAC layer to be capable of utilizing shared channel resources efficiently. The scheduler allocates radio resources dynamically to the users in DL-SCH and UL-SCH transport channels. There are different schedulers for downlink and uplink. Traffic volume, QoS requirements and radio bearer requirements are considered in scheduling decisions. Also the radio conditions can be taken into account through measurement reports by UE. Typically, radio resource allocation is valid for the duration of one TTI. Resource assignment consists of PRBs and MCS. When CA is configured for an UE, multiple serving cells can be scheduled simultaneously. Additionally, cross carrier scheduling can be employed using Carrier Indicator Field (CIF).

The resource allocation for both downlink and uplink are signalled via PDCCH and therefore UE monitors it while in RRC_CONNECTED state. The UEs are identified with C-RNTI assigned by E-UTRAN. If CA is used, the same C-RNTI applies for all component carriers. If retransmission is needed it is also signalled via PDCCH. [7]

In Carrier Aggregation, the Release 10 UEs can be assigned with all component carriers the UE capabilities allow, while Release 8 UEs are assigned only one CC. The RRM has to select proper CC for each Release 8 UE. If there are multiple users at each component carrier, the packet scheduler should be channel aware in frequency domain to be able to maximize the system capacity. [36] The resource sharing over two or more frequencies helps maximizing the system capacity. Pooled resources are less vulnerable for restrictions caused by uneven load distribution between cells. The eNodeB scheduler can offload traffic from high load cell to low load cell, which helps maintaining good signalling capacity in both cells. [5] From Release 10 onwards, there are two scheduling methods available:

1. Normal scheduling (PDCCH and PDSCH are transmitted within the same cell)
2. Cross carrier scheduling (PDCCH can be transmitted within different cell than the corresponding data channel) [32]

To support the Cross Carrier Scheduling (CCS), PDCCH was modified by adding Carrier Information Field (CIF) to indicate the correct downlink carrier's resources are being allocated. CCS allows more dynamic utilization of PDCCH resources as the PDCCH signalling capacity is pooled from the UE point of view. Cross carrier scheduling is also useful with heterogeneous networks, where overlapping PDCCH regions may interfere each other. With HetNets it is possible to define macro cell to provide control channel with user plane data and micro cells to provide only user plane data for additional capacity. [5] CCS is also an effective method for offloading data transmission from narrowband carrier to wideband carrier [34]. Cross carrier scheduling offers several benefits:

- In an interference limited situation, eNodeB can configure the resource allocation of the interfered cell through another less interfered cell. With conventional scheduling, the configuration message might not reach the corresponding cell.
- CCS improves the flexibility in scheduling operation.
- With CCS, the number of PDCCHs UE has to monitor can be less than the number of configured CCs. Thus, UE is not required to decode all the PDCCHs, which reduces the processing significantly. [32]

Cross carrier scheduling is not used for PCell. Therefore, SCell PDCCH cannot transfer the resource allocation information of the PCell. CCS is configured using the *CrossCarrierSchedulingConfig* parameter included in the *RRCConnectionReconfiguration* message. [32]

4.5 Mobility Evolution

Mobility in Carrier Aggregation is mostly similar to the Release 8 LTE. In this section, the cell management functionality and the enhancements to connected state mobility are discussed. Cell management is a new functionality that has to be performed in co-operation with mobility management. Actions in both cell and mobility management are based on UE measurements. [34] Here, cell management relates to SCell activation and deactivation procedures. Also, the connection setup is discussed in the Section 4.5.1. Mobility management presents the handover procedure and the mobility measurements in Section 4.5.2.

4.5.1 Cell Management

The essential feature in CA is that multiple cells can be configured for connected state UE. The UE can therefore exploit the bandwidth of all serving cells. In Release 8 LTE, the Physical Cell Identity (PCI) is used for deriving the security key. In CA there are multiple serving PCIs that can be chosen for security key derivation. In Release 10 it is defined that in CA one of the cells will act as Primary Cell (PCell). When UE initiates RRC connection to eNodeB, the particular cell becomes PCell. Control information messages (such as security, measurements and mobility) are transmitted via PCell.

The additional serving cells are referred as Secondary Cells (SCell), which namely provide additional radio resources to the UE. Due to this nature, many of the UE procedures are not applied to the SCell. These include e.g. radio link monitoring, random access procedure and semi-persistent scheduling. SCells can be changed without handover. [32]

After successful RRC connection establishment UE has one configured serving cell: PCell. Secondary Cells are configured only in RRC_CONNECTED state and if there is sufficient amount of data in the buffer, one or more SCells can be added via RRC Connection Reconfiguration procedure. The same procedure is used for adding, modifying and removing SCells. [32] A live network SCell configuration trace is presented in Section 5.4.1.

Cell activation and deactivation mechanisms are implemented in LTE-A to reduce UE power consumption. Release 8 introduced Discontinuous Reception (DRX) that allows UE to enter power saving mode when no transmission or reception is on-going. DRX state is common to all serving cells. Release 10 enables the UE or the network to activate and deactivate SCells. If the cell is deactivated, it cannot transmit or receive any signals. The network can issue activation or deactivation command in the form of MAC control element, and the UE can deactivate SCell after timer expires. Activation and deactivation procedures can be performed independently for each SCell. PCell cannot be deactivated as it is the RRC signalling gateway towards the network. [34]

A separate activation step is required to reduce the signalling overhead caused by frequent activation and deactivation of SCells. PCells are never deactivated as they maintain the connected state between UE and eNodeB. The activation and deactivation of SCells are implemented in MAC layer signalling instead of RRC signalling. Using MAC signalling reduces the delay in activation and deactivation procedures. The UE needs to perform only RSRP and RSRQ measurements on deactivated SCell. The power consuming CSI measurements are omitted. Also, the uplink CA transmission on SCell is disabled after SCell deactivation. [32]

MAC Control Elements (CE) for activation and deactivation of SCells was introduced in Release 10 to handle the cell management. It includes *SCellIndex* indicator to determine which SCell is to be activated or deactivated. Each SCell can also be deactivated via specific deactivation timer: *sCellDeactivationTimer*. If no explicit deactivation command is received, the deactivation timer disables SCell after expiry. When SCell is already configured, but deactivated, the UE should be able to activate the SCell within 8 ms. If the UE received MAC CE for activation in subframe n, the SCell operation should start in subframe $n+8$. The same 8 ms requirement applies also for deactivation. [32] SCell activation and deactivation operations is presented in Figure 16.

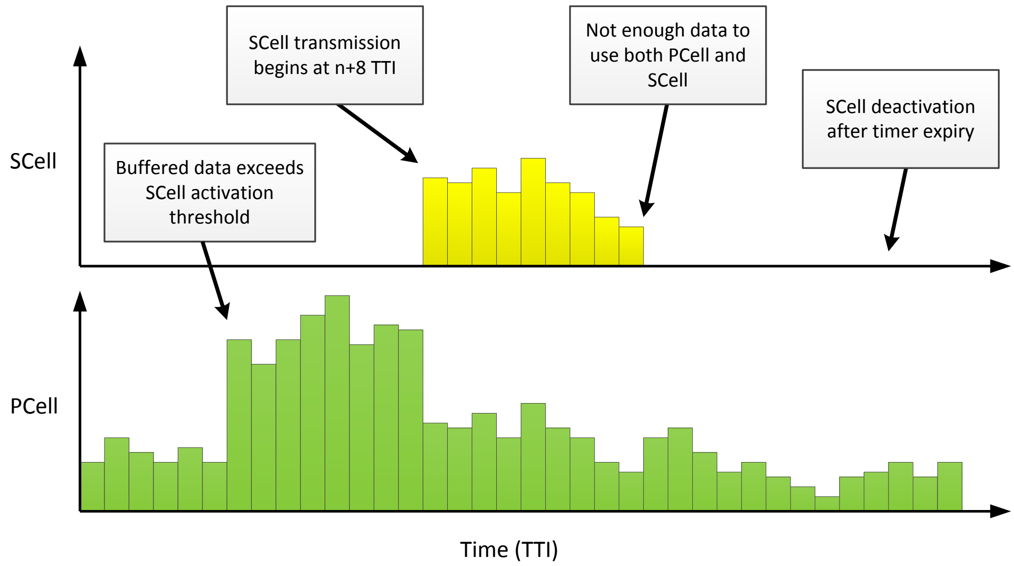


Figure 16: Secondary cell activation and deactivation [5]

3GPP specification [26] defines requirements for SCell activation and deactivation delay in Carrier Aggregation. The requirements are applicable for both FDD and TDD operation. The delay refers to UE processing time and it depends upon specific conditions. The activation includes turning on another RF chain in the UE and transmitting a CSI report to the eNodeB. If the UE has recently sent a measurement report for the SCell being activated and the SCell remains detectable during activation, the procedure should not take more than 24 ms. Otherwise, the procedure should not take more than 34 ms. The interruption in PCell data transmission should not occur within 5 ms before activation command and 9 ms after the command for FDD. The maximum length for interruption is 5 ms for intra-band CA and 1 ms for inter-band CA. For TDD, the interruption should not occur within 5 ms before activation command and 11 ms after the command. UE shall send CSI message indicating it is *out of range* until the SCell activation is completed. [26]

4.5.2 Mobility Management

LTE-A mobility is managed with RRC layer messaging. The procedures include SCell addition, removal and modification. The cell addition is also referred as cell configuration for the UE, which is different operation than activating SCell. Typically, any component carrier may act as a PCell. As the control information traverses through the PCell, it is critical that the PCell radio connection remains at satisfying level. To improve the link quality, the PCell can also be changed by the network (handover). PCell can also be changed due to load balancing between cells. [34]

In RRC_CONNECTED state, the UE measures PCell to determine need for cell changes. In CA, there is always only one PCell configured for the UE. Therefore, the UE does not need to perform any extra measurements compared to Release 8 LTE mobility. If cell change criteria is met and measurement event A3 occurs, the source eNodeB requests the target eNodeB for handover. In CA, the PCell is changed only via handover. Depending on the target eNodeB capabilities, different handover possibilities exist. If the target eNodeB is CA capable the SCells can be reconfigured after handover. SCells are removed if there is no CA capability. [5]

The SCells are deactivated for the duration of handover. The deactivation command is typically included in the same *RRCConnectionReconfiguration* message as the handover command. The SCells remain deactivated until UE receives activation command from the target eNodeB. A handover trace from live network is presented in Section 5.4.3. Additionally, the delay in SCell configuration after handover is studied in Section 5.4.4.

The eNodeB updates a list of SCell candidates based on the measurement reports. A list entry includes Physical Cell Identifier (PCI), carrier frequency (EARFCN), received signal power (RSRP) and received signal quality (RSRQ) information. The source eNodeB forwards the list of SCell candidates to the target eNodeB during handover preparation. The target cell uses the list for configuration of SCells after the handover. [32]

The selection of PCell has not changed from the Release 8. However, the selection of SCell was not covered in Release 8 and thus additional signalling was included in Release 10 to assist the handover. In Release 10, the UE reports the best neighboring cell on each serving frequency. The UE transmits *reportAddNeighMeas* information to indicate the neighboring cell identity. The measurement report also includes RSRP and RSRQ results from the neighboring cells. If the measurement event conditions are reached, the best neighboring cell of serving frequency is configured for the UE. [32]

If SCell is added or modified, *RRCConnectionReconfiguration* message includes a specific *sCellToAddModList* parameter. If the message includes *sCellToReleaseList* parameter, then SCell is to be removed. SCell management includes the following parameters:

- *cellIdentification*: contains SCell PCI and EARFCN
- *sCellIndex*: identifies each SCell configured for the UE. In Layer 1 it refers to the corresponding SCell to which the resource allocation information over the PDCCH applies. In MAC layer the index corresponds to the bit position of Extended Power Headroom MAC CE and SCell Activation and Deactivation MAC CE. In RRC layer, it informs whether the SCell is to be removed or modified.
- *radioResourceConfigCommonSCell*: contains common system information of the SCell, including physical layer configuration parameters.
- *radioResourceConfigDedicatedSCell*: contains UE specific configuration information of the SCell. [32]

The mobility measurement procedure is basically the same in Carrier Aggregation as in Release 8 LTE. The eNodeB sets the measurement targets for each component carrier in order to receive measurement reports. Measurements are also performed on the frequency layers of the configured SCells to determine if SCell should be changed. Idle state operation is unchanged compared to Release 8 as the CA is active only in connected state. [5]

The measurement thresholds and offsets are configured by the network. [34] The measurement events are presented in Table 2.

Table 2: Measurement events in LTE-A

Event A1	Serving cell becomes better than threshold
Event A2	Serving cell becomes worse than threshold
Event A3	Neighbor cell becomes offset better than PCell
Event A4	Neighbor cell becomes better than threshold
Event A5	PCell becomes worse than threshold 1 and neighbor cell becomes better than threshold 2
Event A6	Neighbor cell becomes offset better than SCell
Event B1	Inter-RAT neighbor cell becomes better than threshold
Event B2	PCell becomes worse than threshold 1 and inter-RAT neighbor cell becomes better than threshold 2

Measurement event A6 was introduced in the Release 10. It is used for detecting and reporting stronger cell within the same frequency than the current SCell. For detecting stronger cell in the PCell frequency, the event A3 is employed as in Release 8. Otherwise, the required measurement events were specified in Release 8. These events were extended in Release 10 by adding the serving cell information on all messages (excluding A4 and B1, which do not need the information). Release 10 retains the s-measure principle of LTE. If the RSRP of serving cell (PCell) is sufficiently high (*s-Measure* parameter), the neighboring cell measurements are omitted to reduce power consumption. [32] Figure 17 illustrates the difference between A3 and A6 events.

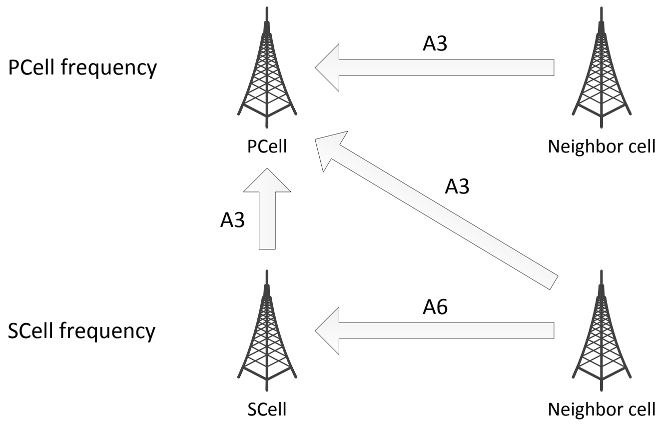


Figure 17: A3 and A6 measurement events [5]

The network is responsible for configuring and reconfiguring SCells to the UE. The SCell management can use measurement reports for decision making. The SCell management includes the following procedures:

- SCell Addition: Event A4 may trigger a measurement report of new detected SCell candidate on another frequency, which can be configured for the UE.
- SCell Removal: Event A2 can trigger a report, which tells that the measured level of SCell frequency has degraded and the cell should be removed from the UE.
- SCell Activation: Event A1 can trigger a report, which tells that the measured SCell level is now sufficient for data transfer and can be activated.
- SCell Deactivation: Event A2 can be used similarly to SCell Removal.
- SCell Replacement: Event A6 is used for detecting SCell candidates with higher received power levels than current SCell and can trigger the replacement with another SCell. [32]

UE is required to measure the serving cell, intra-frequency adjacent cells and inter-frequency adjacent cells. The measurement framework in Release 10 was extended to support multiple serving cells. The following measurements are required in E-UTRAN:

- Serving cell measurements of all serving cells (PCell and SCells)
- Intra-frequency measurements for each serving cell frequency
- Inter-frequency measurements for other frequencies than serving cells

4.6 Performance

Carrier Aggregation produces performance gains in following ways:

- Improved peak data rates through increased bandwidth
- Resource sharing and load balancing
- Frequency domain joint scheduling [5]

IMT-Advanced performance requirements were presented in Section 3.1. The spectral efficiency requirements were 15 bit/s/Hz for downlink and 6.75 bit/s/Hz for uplink. 3GPP defined higher targets for LTE-Advanced. The system should support 30 bit/s/Hz peak spectral efficiency for downlink (assuming 8×8 MIMO) and 15 bit/s/Hz for uplink transmission (assuming 4×4 MIMO). [35]

The requirement for low mobility data rate is 1 Gbit/s and for high mobility 100 Mbit/s [27]. The possible peak data rates for LTE-A are presented in Section 4.6.2. New UE categories were specified in LTE-A to support the new features. They are presented in Section 4.6.1. Furthermore, the radio resource management and scheduling are discussed in Section 4.4.

4.6.1 UE Capabilities

The number of aggregated Component Carriers (CC) and the possible data rates depend on the capabilities of the UE [7]. 3GPP Release 10 introduced three new UE categories that support Carrier Aggregation. The Category 6 and 7 UEs support maximum of 300 Mbit/s downlink data rates by using either 4×4 MIMO or 2×2 MIMO with 2×20 MHz CA. The Category 8 was specified purely for marketing purposes. However, it illustrates the possibilities of LTE-A, by combining 5×20 MHz CA with 8×8 MIMO in downlink and 4×4 MIMO in uplink. Release 11 introduced four categories (9, 10, 11 and 12) to support DL data rates of 450 Mbit/s and 600 Mbit/s. Their capabilities can be found from [37]. Table 3 summarizes the key features of the UE categories.

The theoretical peak throughput for user data transmission can be calculated using Transport Block Size (TBS) and Modulation and Coding Scheme (MCS) given in [15]. Transport block is transmitted in one subframe, which has the length of one TTI (1 ms). One radio frame consists of 10 subframes (equals 10 ms). The network assigns UE a suitable MCS according to the CQI reported by UE. MCS value determines whether QPSK, 16QAM or 64QAM modulation is used. 64QAM offers the highest performance, but it is used only in good radio environment. MCS indicator also determines the TBS, which have pre-determined values. [15] [37]

For example, Category 6 UE that utilizes LTE-A capabilities is able to receive I(MCS) = 28. That refers to 75376 bits per TTI using 100 PRBs or 150752 bits per TTI using 200 PRBs (CA with 2×20 MHz bandwidth) [15]. With 2×2 MIMO that translates to 301504 bits per TTI. Hence, the theoretical peak bit rate in downlink is 301504000 bit/s (302 Mbit/s).

Table 3: UE Categories in Release 10 [37]

	Release 8		Release 10		
	Cat 3	**Cat 4**	**Cat 6**	**Cat 7**	**Cat 8**
Peak data rate DL	100 Mbit/s	150 Mbit/s	300 Mbit/s	300 Mbit/s	3000 Mbit/s
Peak data rate UL	50 Mbit/s	50 Mbit/s	50 Mbit/s	100 Mbit/s	1500 Mbit/s
Max bits received per subframe	102048	150752	301504	301504	2998560
Max bits transmitted per subframe	51024	51024	51024	102048	1497760
Max RF bandwidth DL	20 MHz	20 MHz	40 MHz	40 MHz	100 MHz
Max RF bandwidth UL	20 MHz	20 MHz	20 MHz	40 MHz	100 MHz
Modulation DL	64QAM	64QAM	64QAM	64QAM	64QAM
Modulation UL	16QAM	16QAM	16QAM	16QAM	64QAM
MIMO DL	2×2	2×2	2×2 or 4×4	2×2 or 4×4	8×8
MIMO UL	No	No	No	2×2	4×4

4.6.2 Data Rates

The LTE data rates in general depend on modulation scheme, allocated number of resource blocks, channel encoding and number of transmit antennas (MIMO). [4]

The peak downlink data rate in Release 8 LTE is 150 Mbit/s, which is achieved using single 20 MHz carrier, 64QAM and 2×2 MIMO scheme. Using two 20 MHz component carriers, the data rate essentially doubles to 300 Mbit/s. Using the highest order MIMO scheme (8×8) and full 100 MHz spectrum, the maximum theoretical data rate is 3 Gbit/s.

The theoretical downlink peak data rates using different bandwidths and MIMO schemes are presented in Figure 18. In practice, the peak data rates can be achieved only in excellent radio conditions. However, the cell edge user also benefits from the CA in downlink data transfer, as it was discovered in the performance measurements in Section 5.3.

The peak uplink data rate with Release 8 LTE is 50 Mbit/s. Using 2×20 MHz CA and 16QAM, the uplink peak data rate improves to 100 Mbit/s. If 2×2 uplink MIMO and 64QAM were supported, the peak data rate with two carriers could be as high as 300 Mbit/s. Furthermore, if the maximum of 4×4 uplink MIMO and full 100 MHz spectrum were utilized, the data rate would increase to 1.5 Gbit/s.

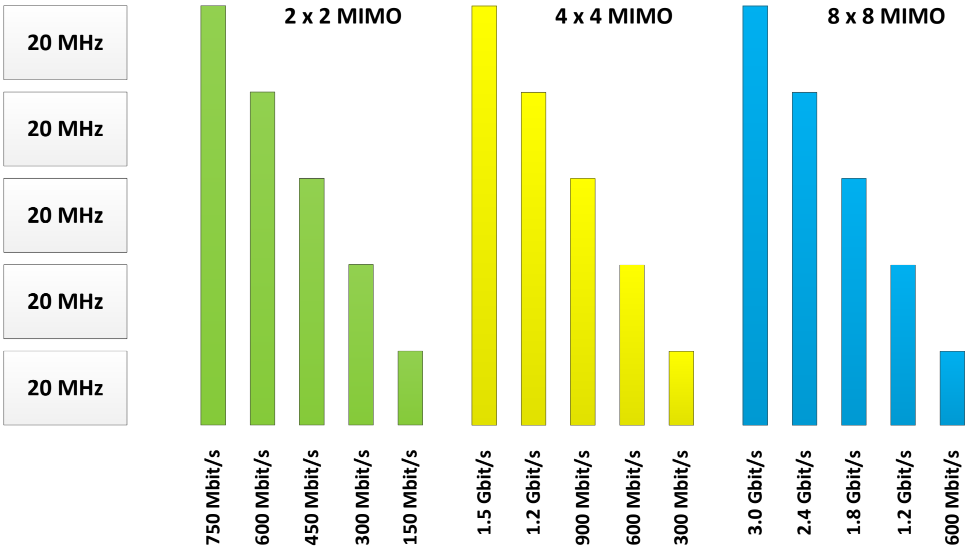


Figure 18: Theoretical maximum data rates in downlink depending on available bandwidth and MIMO scheme [15]

Practically, there are significant challenges in implementing uplink CA and uplink MIMO into the UE. The uplink Tx power is limited and the cell edge users typically do not experience any performance improvements. The UE at cell edge cannot exploit increased bandwidth as it has to distribute all the available power to one carrier to ensure flawless uplink transmission. [5]

4.7 Band Combinations

3GPP specification includes variety of possible band combinations for LTE-A Carrier Aggregation operation. LTE bands are region specific and therefore only subset of the combinations are available in a given region. The 2CC downlink band combinations were specified in the first phase, and the first set of combinations were included in 3GPP Release 10. The band combinations are defined on top of the specification and they are release independent. Therefore, they can be implemented in the UE by adding the band specific performance requirements and required signalling extensions. [5] 3GPP updates the list of CA band combinations [38] regularly.

It can be assumed that in the future the number of possible band combinations in CA will be high. UEs probably cannot support all of them, which leads to fragmentation in UE capabilities. Some combinations are more difficult to implement than others. E.g. 900 MHz and 1800 MHz combination could be problematic due to harmonic distortion. Generally, band combinations with one low band and one high band are easier to implement as the filter requirements are more relaxed.

Table 4 lists all intra-band contiguous combinations defined at the time Release 12 specification was frozen (March 2015). Three component carrier CA was already possible in early 2015 using TDD bands 40 or 41. In total, there were 11 intra-band contiguous combinations [38].

Table 4: Intra-band contiguous CA combinations (2DL/3DL+1UL) [38]

Configuration	**Frequencies**	**Max CCs**	**Max bandwidth**
CA_1 (FDD)	2100 MHz	2	40 MHz
CA_3 (FDD)	1800 MHz	2	40 MHz
CA_7 (FDD)	2600 MHz	2	40 MHz
CA_12 (FDD)	700 MHz	2	15 MHz
CA_23 (FDD)	2000 MHz	2	20 MHz
CA_27 (FDD)	850 MHz	2	13 MHz
CA_38 (TDD)	2600 MHz	2	40 MHz
CA_39 (TDD)	1900 MHz	2	35 MHz
CA_40 (TDD)	2300 MHz	3	60 MHz
CA_41 (TDD)	2500 MHz	3	60 MHz
CA_42 (TDD)	3500 MHz	2	40 MHz

Table 5 lists all intra-band non-contiguous CA combinations. Non-contiguous intra-band CA is interesting for operators, whose spectrum is fragmented. Non-contiguous CA enables utilizing full potential of smaller pieces of spectrum. There were 8 possible band combinations for intra-band non-contiguous CA at the time of Release 12 freeze.

Table 5: Intra-band non-contiguous CA combinations (2DL+1UL) [38]

Configuration	**Frequencies**	**Max CCs**	**Max bandwidth**
CA_2_2 (FDD)	1900 MHz	2	40 MHz
CA_3_3 (FDD)	1800 MHz	2	40 MHz
CA_4_4 (FDD)	1700 MHz	2	40 MHz
CA_7_7 (FDD)	2600 MHz	2	40 MHz
CA_23_23 (FDD)	2000 MHz	2	15 MHz
CA_25_25 (FDD)	1900 MHz	2	40 MHz
CA_41_41 (TDD)	2500 MHz	2	40 MHz
CA_42_42 (TDD)	3500 MHz	2	40 MHz

Table 6 lists few interesting FDD inter-band combinations for 2 DL component carriers that could be utilized in ITU-R Region 1 (e.g. Europe). CA solutions using two inter-band frequencies were being deployed already in 2014, which inspired several operators also to launch their LTE-Advanced networks commercially. By the time of Release 12 freeze in 2015, the specification included 59 2 DL CC combinations in total.

Table 6: Inter-band non-contiguous CA combinations (2DL+1UL) [38]

Configuration	**Frequencies**	**Max CCs**	**Max bandwidth**
CA_1_3 (FDD)	2100 and 1800 MHz	2	40 MHz
CA_1_7 (FDD)	2100 and 2600 MHz	2	40 MHz
CA_1_8 (FDD)	2100 and 900 MHz	2	30 MHz
CA_1_20 (FDD)	2100 and 800 MHz	2	40 MHz
CA_3_7 (FDD)	1800 and 2600 MHz	2	40 MHz
CA_3_8 (FDD)	1800 and 900 MHz	2	30 MHz
CA_3_20 (FDD)	1800 and 800 MHz	2	30 MHz
CA_7_20 (FDD)	2600 and 800 MHz	2	30 MHz
CA_8_20 (FDD)	900 and 800 MHz	2	20 MHz

Table 7 presents several inter-band non-contiguous band combinations for 3 DL CC. The combinations consist of frequencies that are used in ITU-R Region 1 (e.g. Europe) and each frequency band is defined to use FDD. In Europe, LTE is deployed primarily on bands 3, 7 and 20. Therefore the combination of those three bands is the most interesting for the operators and likely to be used in the first phase of three carrier CA deployment. The bands 1 and 8 are typically used for GSM and WCDMA. In near future, they might be allocated for LTE and used in later phase of three carrier CA deployment.

In total, there were 18 band combinations for 3 DL CC specified by the time of Release 12 freeze.

Table 7: Inter-band non-contiguous CA combinations (3DL+1UL) [38]

Configuration	**Frequencies**	**Max CCs**	**Max bandwidth**
CA_1_3_8 (FDD)	2100, 1800 and 900 MHz	3	50 MHz
CA_1_3_20 (FDD)	2100, 1800 and 800 MHz	3	60 MHz
CA_1_7_20 (FDD)	2100, 2600 and 800 MHz	3	50 MHz
CA_3_7_20 (FDD)	1800, 2600 and 800 MHz	3	60 MHz

The band combinations specified for the downlink CA are under investigation also for uplink CA. Using multiple uplink carriers would cause additional interference problems on some band combinations and therefore utilizing them requires careful planning. The downlink band combinations were specified in the first phase as they are easier to implement in practice. The uplink CA has more issues due to following:

– Maximum transmission power limitation results to 3 dB lower power per uplink carrier compared to single carrier transmission

– Two transmitters may cause more out of band emissions and therefore additional power reduction could be required

– In some cases the uplink transmission band is too close to the downlink reception band and could cause power leakage (e.g. 2100 MHz band uplink edge frequency is 1920 MHz and 1800 MHz band downlink edge frequency is 1880 MHz). However, such band combination is not likely to be defined. [5]

4.8 Future Development

According to Cisco analysis [1] the mobile data traffic grew 69 % in 2014. The growth is expected to continue and the estimated growth rate for 2014–2019 is 57 % annually. Figure 19 illustrates the growth rate for the next five years. The mobile video traffic will increase 13-fold during that period and it will account for 72 % of total mobile data traffic by 2019. [1] Ericsson has estimated that there will be 2.6 billion LTE subscriptions by the end of 2019. They expect mobile data traffic to increase 10-fold by the end of 2019. [2] The consensus in the industry is that the mobile data traffic will continue to grow at tremendous rate during next few years. The growth will be dominated by video streaming. Voice over LTE (VoLTE) traffic will account only for small share of the total mobile data traffic [1]. The network operators face the pressure of upgrading their network capacity. Therefore, the 3GPP and the network vendors are constantly trying to innovate new technologies. This section presents few the new technologies that could be implemented in the commercial networks in the near future. Also, the upcoming improvements to Carrier Aggregation are discussed.

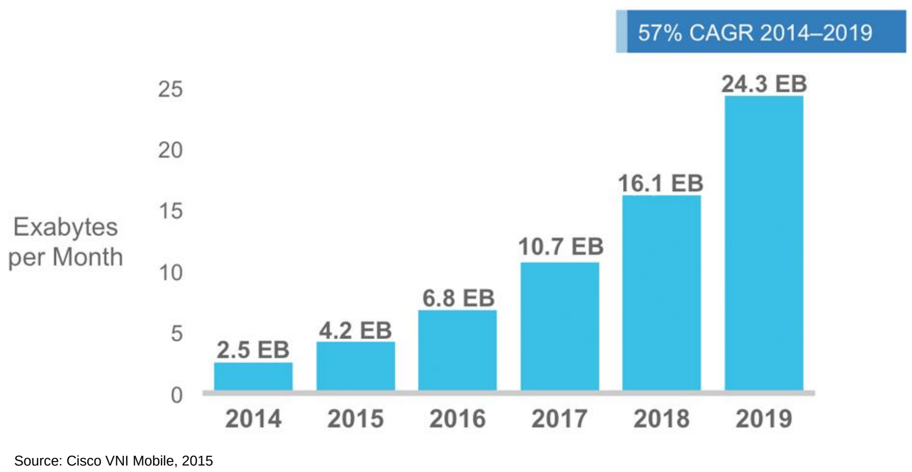


Figure 19: Cisco forecast for mobile traffic growth in 2014–2019 [1]

3GPP has already specified many features that are still waiting for implementation into live networks. In the near future, we will see more these LTE-A technologies deployed. Such features are e.g. FDD-TDD joint operation in CA, higher order MIMO for both uplink and downlink, CA evolution by increasing the number of possible band combinations and component carriers, uplink CA and Coordinated

Multipoint transmission for both uplink and downlink. Possibility to utilize both FDD and TDD bands in CA was introduced in Release 12. [39] The first set of 3 DL CA configurations were also specified at the time of Release 12 freeze. Currently, several 4 DL CA configurations are under discussion in 3GPP. [40]

The 3GPP is currently working with Release 13 specification. One key working item is the utilization of unlicensed spectrum and interworking of LTE and Wi-Fi. The opportunistic use of unlicensed spectrum is seen as important addition to operators existing licensed spectrum. The first option is to aggregate LTE and Wi-Fi bands. That would require specifications for mobility procedures and for a new interface between eNodeB and Wi-Fi access point. The second option is LTE over unlicensed spectrum, which would mean LTE coexisting with other systems in unlicensed band. The 3GPP works in cooperation with IEEE in the matter. [40]

Other important work item considers improvements to CA. 3GPP targets for supporting up to 32 component carriers for both downlink and uplink. [40] That would require solving few issues regarding signalling overhead and physical channel design. The solutions would probably not be fully backward compatible towards Release 8 [34]. Additionally, further improvements are planned for MIMO and also machine-type communications are to be developed. [40]

Eventually, the industry will shift its focus towards 5G networks. There few challenging trends that can be identified at this point. Macro network capacity cannot increase infinitely. As already discussed in Section 3.2.2, the form of networks will be more and more heterogeneous. The mobile performance metrics will evolve towards more user oriented approach. In future networks, the user is able to move seamlessly between different network layers and should not be aware of what type of connection is being used. Also, the importance of energy efficiency will increase. The variety in radio access technologies and wireless devices will grow. One wireless terminal has to manage multiple radio systems and transceivers have to support increased number of frequencies. [41] There has already been research on millimeter wave frequencies (ranging from 3 to 300 GHz), which could solve the spectrum scarcity. [42]

Nokia has argued in its own technology vision [43] that the future mobile networks should provide 1000 times more capacity to be able to accommodate the traffic growth. The additional capacity could be achieved by allocating 10 times more spectrum for mobile use, improving spectral efficiency 10 times and deploying 10 times more cells. The amount of available spectrum could be increased by re-farming present GSM and WCDMA band for LTE, allocating new spectrum from e.g. 3.5 GHz band and by utilizing the unlicensed spectrum at 2.4 GHz and 5 GHz bands. The spectral efficiency could be improved by employing massive MIMO, CoMP and advanced interference cancellation techniques. The network density can be increased by deploying small cells and relays, essentially transforming the macro network into heterogeneous network. [43]

5 Performance Evaluation

Theoretically, Carrier Aggregation should provide a significant upgrade to the radio network performance. This has been proven in simulations [44], [45] and in early laboratory and field tests [46], [33]. In this study, the actual CA performance is evaluated in a production network using professional measurement equipment.

Measurements were conducted in stationary outdoor and indoor locations. Also, mobility characteristics were tested. Different locations were used to determine the effect of radio conditions to the performance. The performance is mainly presented in terms of throughput over the LTE-Uu interface, although CA also enables more dynamic resource sharing at eNodeB.

The results and their reliability are further discussed in Section 5.5. The results are compared to other research in this field and also few proposals are presented for future research.

5.1 Measurement Setup

The radio network under study has two LTE frequencies; 1800 MHz (Band 3) and 2600 MHz (Band 7). The bandwidth for both frequencies is 20 MHz, which is the maximum for a single LTE carrier. Thus, the maximum number of allocated PRBs is 200. The network deployment corresponds to the *Scenario 2* in Section 4.1. Thus, the cells are co-located and overlaid. Lower frequency band (1800 MHz) provides better coverage.

The network was parameterized in such way that either cell at a given sector could perform as Primary Cell (PCell). The eNodeB balances the load between the cells. However, in a low load situation with good radio environment, the cell at 2600 MHz frequency is prioritized. PCell is changed via handover. The results are presented individually for the two carriers with labels *PCell* and *SCell*. They also indicate the used frequency. LTE network performance without CA was measured for reference. The reference results are indicated with *non-CA* label. The network had very low background traffic in all measurement situations.

Each CA eNodeB used in measurements utilized transmission power of 51 dBm for 1800 MHz cells and 49 dBm for 2600 MHz cells. The network employed 2×2 Dynamic Open-Loop MIMO and if possible 64QAM scheme for the downlink transmission. Dynamic Open-Loop MIMO refers to the ability to change from *transmit diversity* to *open-loop spatial multiplexing* (Section 2.3.2) depending on the channel conditions.

Performance was evaluated measuring downlink throughput while repeatedly transferring a large text file from FTP server. The throughput was measured from either from physical layer (PDSCH) or from the application layer. In the physical layer it is possible to identify the data streams for all component carriers individually. Thus, the carriers can be compared. However, the data in physical layer includes header information, signalling overhead and erroneous transmissions. Therefore, application layer throughput is used to demonstrate the actual data rate experienced by the user.

The CA measurements were conducted with Category 6 capable mobile devices and the reference measurements (Release 8 LTE) with Category 4 devices in the same locations. Both UE categories employ the maximum uplink Tx power of 23 dBm. The measurement software used was *Nemo Handy* [47] from *Anite* and captured results were then studied with *Nemo Analyze* [48] post-processing tool. The results and figures were produced with statistical computing tool *R* [49].

5.2 Carrier Frequencies

The following measurements utilize two carrier frequencies, which have different characteristics. The differences could have an impact on the system performance. The difference in radio propagation is evaluated using the formula for free space path loss [14]. The path loss in dB is defined in Equation 1.

$$L = 20log_{10}\left(\frac{\lambda}{4\pi r}\right) \tag{1}$$

Here, λ refers to the wavelength and r refers to the distance. Using the same distance it is possible to calculate difference in path loss for the two wavelengths. That is denoted with ΔL. For 1800 MHz the wavelength equals $\lambda_{f1} = 0.1667$ m and for 2600 MHz the wavelength equals $\lambda_{f1} = 0.1154$ m.

$$\Delta L = 20log_{10}\left(\frac{\lambda_{f1}}{\lambda_{f2}}\right) \tag{2}$$

This results to $\Delta L = 3.2$ dB. The difference in maximum DL transmission power is 2 dB. Therefore the total difference in signal strength is 5.2 dB. Additionally, the higher frequencies suffer more from signal scattering if there are obstacles in the propagation path [14]. In practice, the RSRP level should be higher at 1800 MHz band. However, the signal quality at 2600 MHz should be higher as there were less interfering eNodeBs at the proximity of each measurement location. That implicates higher SNR results at 2600 MHz band.

5.3 Stationary Measurements

The stationary measurements in three outdoor locations and one indoor location illustrate the difference of Carrier Aggregation performance in different radio environments. The radio conditions were determined by measuring the Reference Signal Received Power (RSRP) level and Signal-to-Noise-Ratio (SNR) level. RSRP illustrates the signal strength and SNR illustrates the signal quality experienced by the UE. The outdoor measurement were conducted within the coverage area of the same eNodeB. Location A represents good radio conditions, location B poor signal strength and quality, and location C average conditions.

The eNodeB used for outdoor measurements is located in suburban area, with low profile buildings. The antenna height is 29 meters and antenna gain is 18 dBi. The CA and non-CA performances were tested on separate measurements. The eNodeB and its simulated coverage areas for 1800 MHz are presented in Figure 20 along with the measurement locations.

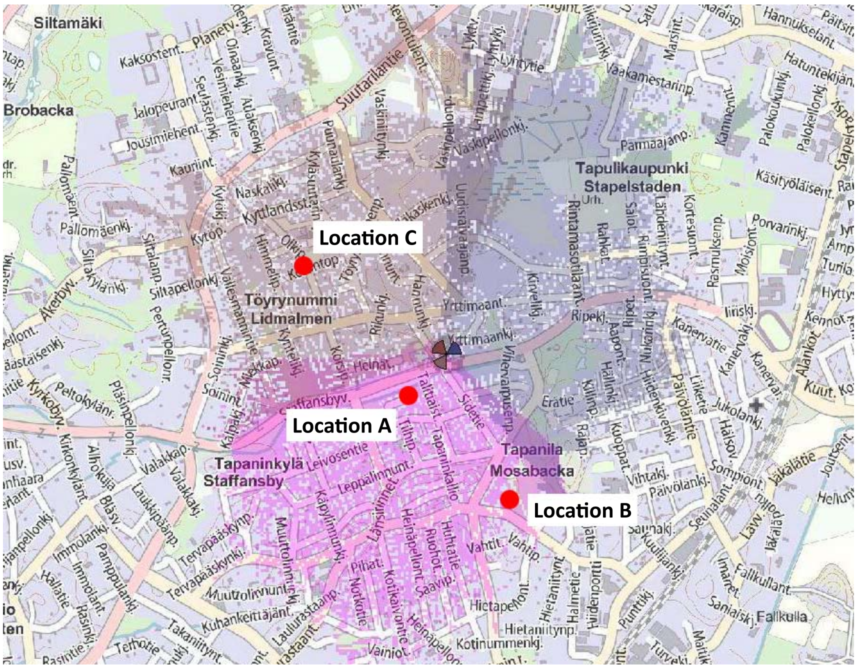


Figure 20: Stationary measurement locations and the eNodeB

5.3.1 Measurement Location A

Measurement location A was chosen in such way that it had excellent radio conditions. There was a line-of-sight from Location A to the eNodeB. The distance from measurement location to the eNodeB was approximately 200 meters. The radio conditions and throughputs are presented in Table 8 and the distribution of modulation and MIMO schemes are presented in Table 9.

Table 8: Key figures from measurement location A

	PCell	**SCell**	**Non-CA**
Frequency	2600 MHz	1800 MHz	2600 MHz
Radio Conditions			
Average RSRP	-75.8 dBm	-58.3 dBm	-75.6 dBm
Average SNR	25.6 dB	21.7 dB	24.6 dB
Throughputs			
PDSCH Average	142.4 Mbit/s	127.4 Mbit/s	126.8 Mbit/s
PDSCH Peak	147.9 Mbit/s	148.3 Mbit/s	147.2 Mbit/s
Application Average	252.3 Mbit/s		113.3 Mbit/s
Application Peak	286.8 Mbit/s		142.9 Mbit/s

The Figure 21 illustrates the radio conditions. SNR averages at 25.6 dB for 2600 MHz (both PCell and non-CA UE), which indicates very low interference from other transmitters. SNR level for 1800 MHz is slightly lower, but still very good at 21.7

Table 9: Modulation scheme and MIMO usage in measurement location A

	PCell	**SCell**	**Non-CA**
Frequency	2600 MHz	1800 MHz	2600 MHz
Modulation			
QPSK	1.7 %	0 %	1.0 %
16QAM	0 %	0 %	0 %
64QAM	98.3 %	100 %	99.0 %
MIMO Scheme			
Tx Diversity	3.5 %	0 %	1.9 %
2×2 *MIMO*	96.5 %	100 %	98.1 %

dB on average. The variance on SNR is rather small and almost all the samples are better than 20 dB. The RSRP for 1800 MHz is significantly better than for 2600 MHz. This is due to larger Tx power and better radio propagation characteristics for the lower frequency. The signal quality and strength are at such high level that there are very few errors in transmission and generally no need for retransmissions.

Due to excellent signal-to-noise ratio, 64QAM was employed almost 100 % of the time for all measurements at location A. Also, the spatial multiplexing (MIMO) was fully utilized.

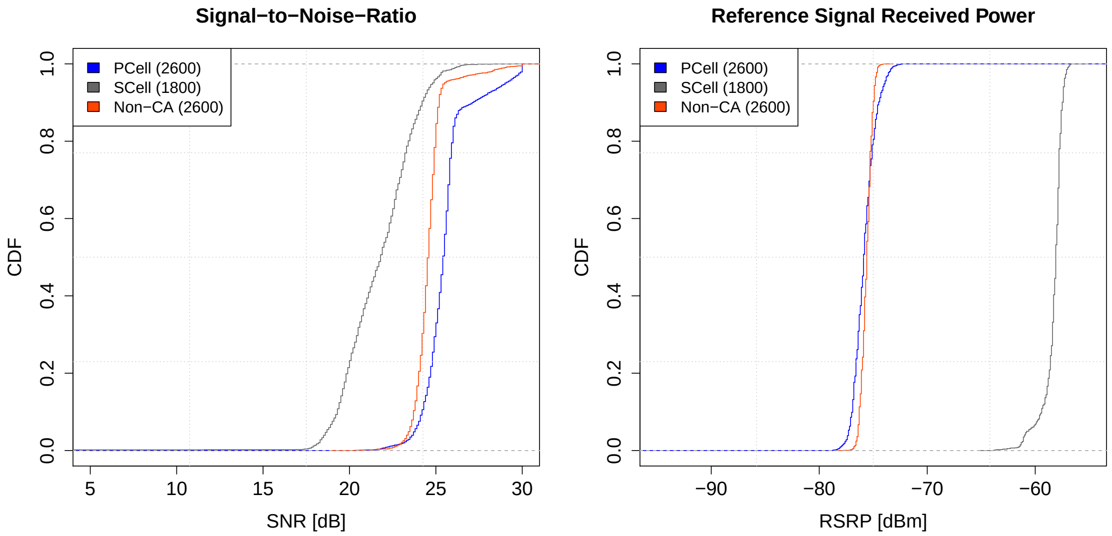


Figure 21: Measurement location A: SNR and RSRP

The Figure 22 presents the distributions of Transport Block Size and Physical Resource Block allocation for the UE. The TBS assigned for the UE follows closely to the Channel Quality Indicator (CQI) reported by the UE. The mapping of CQI to MCS and TBS can be found from [15]. PCell at 2600 MHz frequency was constantly using the maximum TBS, while SCell and non-CA UE used generally slightly smaller blocks. This can be at least partly explained with higher SNR at PCell. On average, PCell TBS is 71 kbit, SCell TBS is 65 kbit and non-CA TBS is 64 kbit. PRBs are allocated based on the load situation on the cell. During the measurement the background traffic was very low. The SCell at 1800 MHz frequency experienced greater variance in terms of resources, and the average number of PRBs was 88. The average PRB utilization for PCell was 95. It can be assumed that the 1800 MHz frequency cell served more UEs and reserved resources for them.

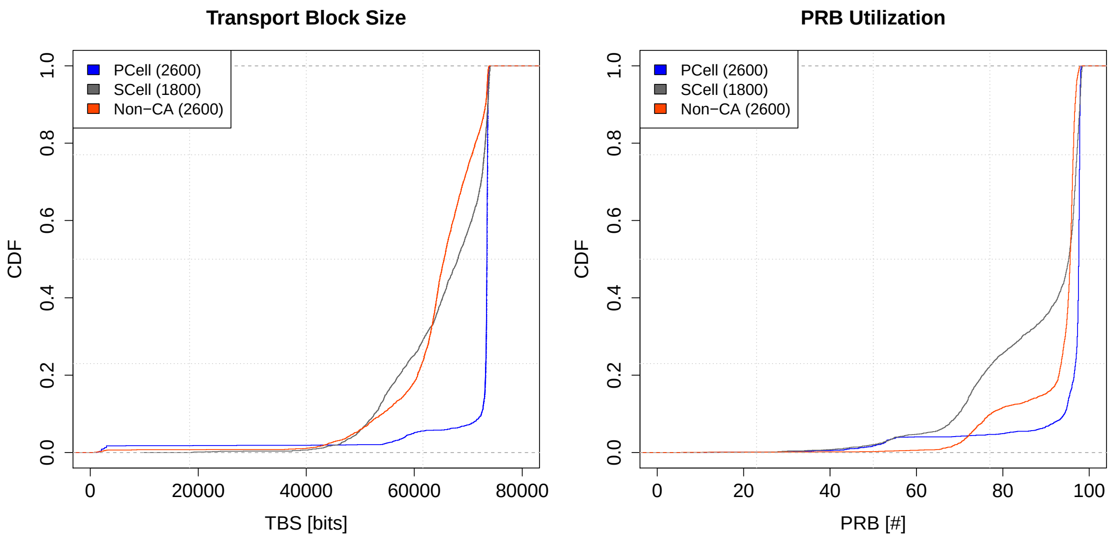


Figure 22: Measurement location A: TBS and PRB usage

Figure 23 presents the PDSCH and application throughputs. Average and peak throughputs are also presented in Table 8.

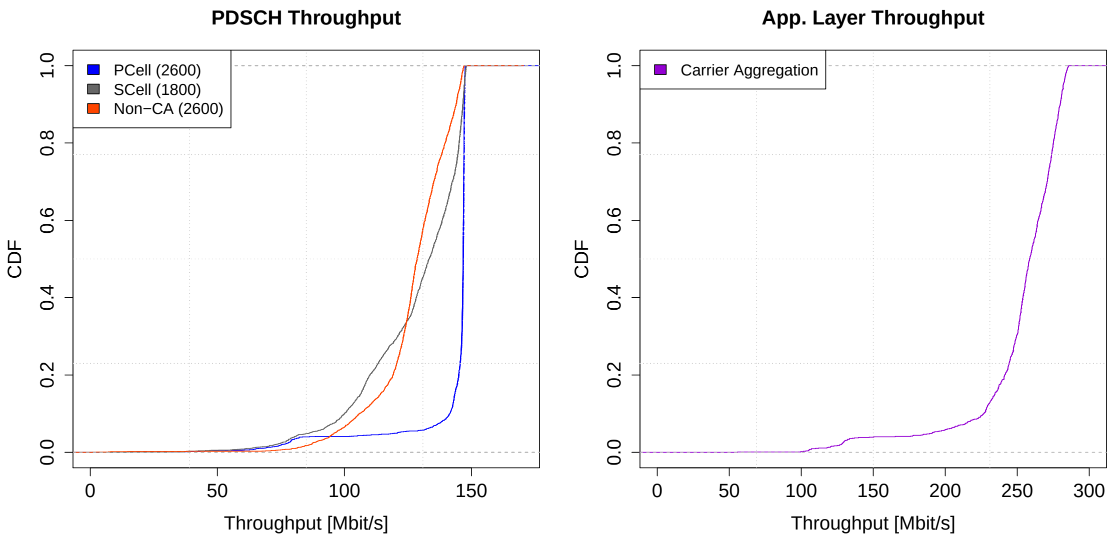


Figure 23: Measurement location A: PDSCH and Application throughput

It can be observed that good radio conditions and low load at the cell results in good downlink throughput. The SNR conditions enable using 64QAM through the entire measurement along with MIMO. PDSCH throughput experienced some variation, but almost all the samples are above 100 Mbit/s. The PCell at 2600 MHz performs better than SCell at 1800 MHz or non-CA (Cat. 4) UE. This is due to greater share of resources assigned by the eNodeB and utilizing larger transport blocks. The throughput is also very stable. In good conditions, the peak application throughput (286.8 Mbit/s) is close to the theoretical maximum (300 Mbit/s) for 40 MHz bandwidth and 2×2 MIMO. The peak throughput for non-CA UE was 142.9 Mbit/s, which is also close to the theoretical maximum for Cat. 4 UE. The CA performance gain for peak throughput is then 101 %.

5.3.2 Measurement Location B

Measurement location B was chosen to represent a cell edge. Location B had no line-of-sight to the eNodeB and it located in between two sectors. The distance between measurement location and eNodeB was approximately 750 meters and there was a small hill between the two points. Both signal strength and signal quality were poor. The radio conditions and throughputs are presented in Table 10 and the distribution of modulation and MIMO schemes are presented in Table 11.

Table 10: Key figures from measurement location B

	PCell	**SCell**	**Non-CA**
Frequency	1800 MHz	2600 MHz	1800 MHz
Radio Conditions			
Average RSRP	-107.7 dBm	-122.4 dBm	-110.5 dBm
Average SNR	2.3 dB	4.9 dB	1.0 dB
Throughputs			
PDSCH Average	19.6 Mbit/s	29.3 Mbit/s	15.8 Mbit/s
PDSCH Peak	32.8 Mbit/s	36.9 Mbit/s	29.2 Mbit/s
Application Average	42.1 Mbit/s		13.3 Mbit/s
Application Peak	61.9 Mbit/s		27.3 Mbit/s

The channel conditions are presented in Figure 24. The difference compared to location A is significant. The SNR has averages of 2.3 dB and 1.0 dB at 1800 MHz. The frequency is used by PCell and non-CA UE respectively. The SNR level for 2600 MHz is slightly higher, however not very good at 4.9 dB on average. There are some variance as all SNR figures vary ± 5 dB during the measurement. Also at location B, the RSRP for 1800 MHz is significantly better than for 2600 MHz. The RSRP at the range of -110 dBm is rather acceptable for LTE data transmission. However, the RSRP of SCell is mostly below -120 dBm, which is very poor and approaches the receiver sensitivity.

The poor SNR levels result to utilization of robust modulation schemes. In all cases, QPSK and 16QAM were employed all the time. The distribution is visible

Table 11: Modulation scheme and MIMO usage in measurement location B

	PCell	**SCell**	**Non-CA**
Frequency	1800 MHz	2600 MHz	1800 MHz
Modulation			
QPSK	66.8 %	49.4 %	69.6 %
16QAM	33.2 %	50.4 %	30.4 %
64QAM	0 %	0.2 %	0 %
MIMO Scheme			
Tx Diversity	71.6 %	82.7 %	98.8 %
2×2 *MIMO*	28.4 %	17.3 %	1.2 %

in Table 11. Additionally, the transmit diversity MIMO scheme was used in major share of the samples to ensure adequate Bit Error Rate (BER).

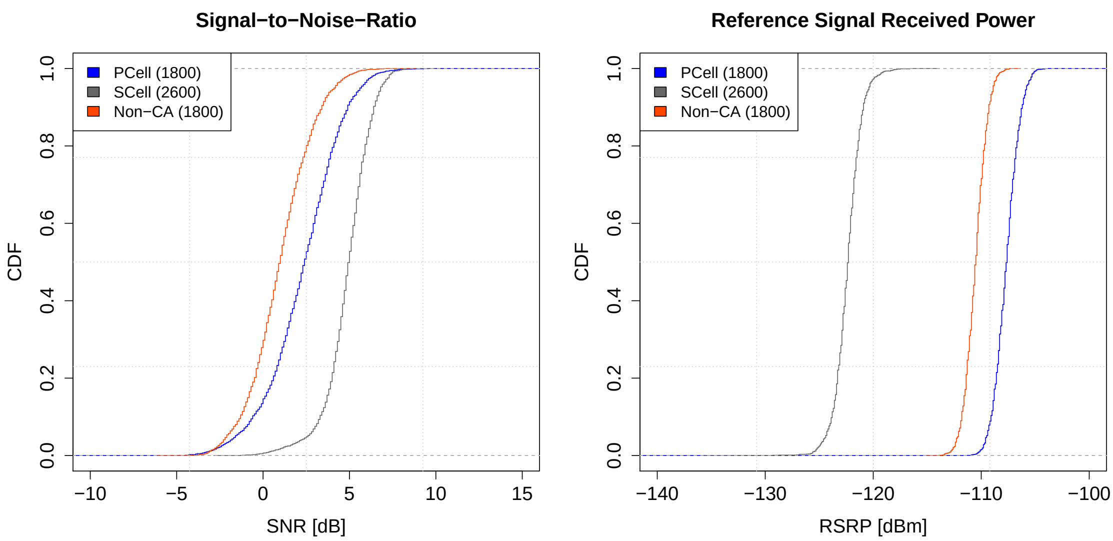


Figure 24: Measurement location B: SNR and RSRP

The Figure 25 illustrates the TBS and PRB utilizations. The lack of 64QAM is visible in transport block size distribution. Low MCS levels correlates to small transport blocks. The variance in TBS was expected as both QPSK and 16QAM were employed for long periods of time. The former is capable of carrying 2 bits/symbol, while the latter can take 4 bits/symbol. The cells at 1800 MHz provide average TBS of 15 kbit. The SCell at 2600 MHz benefits from better SNR conditions as it is able to provide average TBS of 25 kbit.

UE was able to receive almost all resources. The average PRB utilizations were 87 for the PCell, 95 for the SCell and 82 for non-CA UE. The 1800 MHz frequency experienced greater variance and received generally less resources. The SCell at 2600 MHz frequency provided almost all possible PRBs.

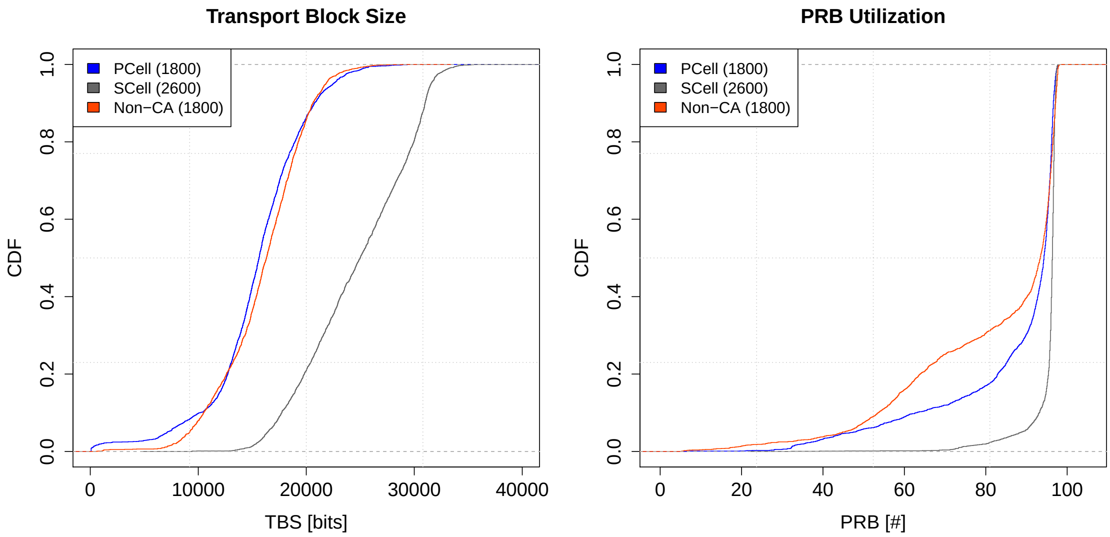


Figure 25: Measurement location B: TBS and PRB usage

The Figure 26 presents the PDSCH and application throughputs. The average and peak throughputs are also presented in Table 8. Despite the poor radio environment, LTE UE can still reach throughput in the range of tens of Mbit/s.

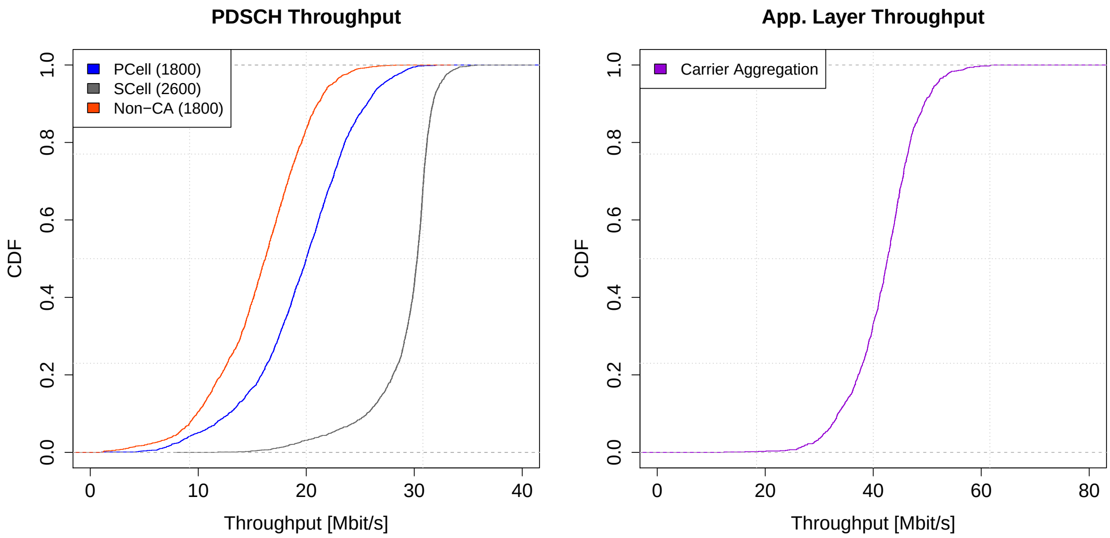


Figure 26: Measurement location B: PDSCH and Application throughput

The SNR conditions limit the modulation scheme to QPSK and 16QAM. Also, transmit diversity was employed during the measurement to secure the transmissions. Therefore, average PDSCH throughputs were limited to 19.6 Mbit/s for PCell and 15.8 Mbit/s for non-CA at 1800 MHz. The SCell at 2600 MHz benefited from the slightly better SNR and the average PDSCH throughput was 29.3 Mbit/s. The variation in throughput is similar to the variation in TBS and PRB usages. The peak application throughput for CA is rather impressive (61.9 Mbit/s) for an UE at the cell edge. The CA UE can utilize secondary carrier with less interference, which is capable of providing better throughput than primary carrier. However, the carrier selection criteria is RSRP, which is better at 1800 MHz, and therefore selected by non-CA UE. In this case, Carrier Aggregation provides 127 % performance gain.

5.3.3 Measurement Location C

Measurement location C had somewhat average radio conditions. Location C had no line-of-sight as there were trees and rooftops along the propagation path. The distance to the eNodeB was approximately 600 meters. The radio conditions and throughputs are presented in Table 12 and the distribution of modulation and MIMO schemes are presented in Table 13.

Table 12: Key figures from measurement location C

	PCell	**SCell**	**Non-CA**
Frequency	1800 MHz	2600 MHz	1800 MHz
Radio Conditions			
Average RSRP	-83.0 dBm	-99.8 dBm	-84.5 dBm
Average SNR	16.9 dB	21.7 dB	15.1 dB
Throughputs			
PDSCH Average	42.7 Mbit/s	116.0 Mbit/s	40.0 Mbit/s
PDSCH Peak	75.3 Mbit/s	144.4 Mbit/s	77.8 Mbit/s
Application Average	137.3 Mbit/s		34.4 Mbit/s
Application Peak	205.6 Mbit/s		59.7 Mbit/s

Table 13: Modulation scheme and MIMO usage in measurement location C

	PCell	**SCell**	**Non-CA**
Frequency	1800 MHz	2600 MHz	1800 MHz
Modulation			
QPSK	1.0 %	0 %	0.8 %
16QAM	84.4 %	0.5 %	83.7 %
64QAM	14.6 %	99.5 %	15.5 %
MIMO Scheme			
Tx Diversity	15.7 %	0 %	28.0 %
2×2 *MIMO*	84.3 %	100 %	72.0 %

The Figure 27 illustrates the radio conditions. It can be observed that the 2600 MHz frequency had significantly better SNR compared to 1800 MHz. There were several eNodeBs nearby using the latter frequency, which probably caused inter-cell interference. As in location B, the 1800 MHz frequency was used by PCell and non-CA UE respectively. The SNR level of 2600 MHz was 21.7 dB on average, while PCell had SNR of 16.9 dB and non-CA UE had 15.1 dB. The SNR for PCell and non-CA varied more than ±5 dB from the average. As in previous locations, the RSRP for 2600 MHz is approximately 15 dB lower than for 1800 MHz frequency.

The differences in SNR result to differences in MCS. SCell could utilize 64QAM practically during the entire measurement, while PCell and non-CA used mostly 16QAM. The distribution is visible in Table 13. SCell was also able to utilize MIMO in 100 % of the samples. PCell and non-CA needed to use the transmit diversity 15–30 % of the time.

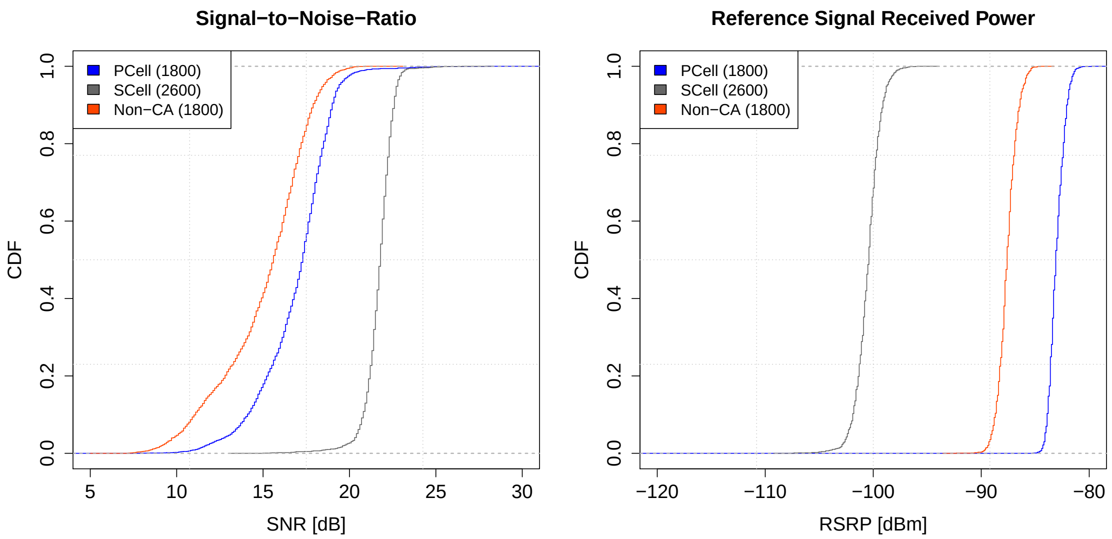


Figure 27: Measurement location C: SNR and RSRP

The transport block sizes and resource utilization are presented in Figure 28. The difference in SNR figures is clearly visible in TBS distribution. SCell operates at 2600 MHz band, which is otherwise unused and can sustain high coding rate. The average TBS is significantly larger, averaging 59 kbit. PCell and non-CA at 1800 MHz suffer from degraded SNR and report low channel quality values to the eNodeB. They are therefore limited to average transport block sizes of 24 and 25 kbit, respectively.

The scheduler allocates almost all the radio resources for UE at 2600 MHz. Meanwhile, the resource allocation at 1800 MHz varies heavily. Generally, the PCell (68 PRBs on average) and non-CA UE (75 PRBs on average) receive less resources than SCell. There could have been more other users at 1800 MHz carrier due to larger coverage area. Nonetheless, the scheduling algorithm favors the UEs in better radio conditions.

The Figure 29 illustrates the physical layer and application layer throughputs. The average and peak throughputs are presented in Table 12. The average PDSCH throughputs were 42.7 Mbit/s for the PCell at 1800 MHz and 116.0 Mbit/s for the SCell at 2600 MHz. The noticeable difference can be explained with the earlier observations. Also, the SCell provided more radio resources for the UE. The average

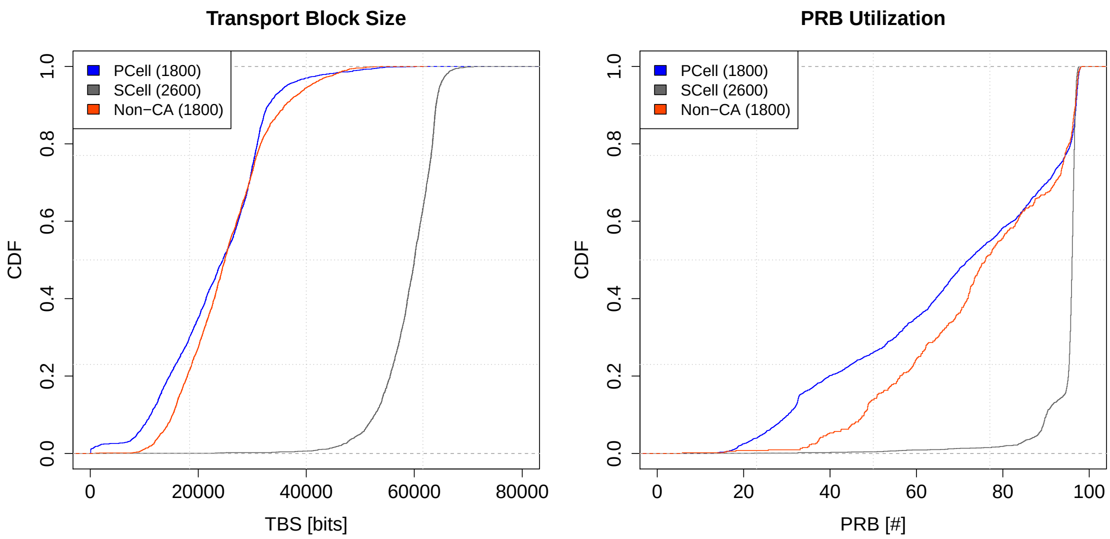


Figure 28: Measurement location C: TBS and PRB usage

PDSCH throughput for non-CA was 40.0 Mbit/s, which is in line with the PCell throughput on the same frequency.

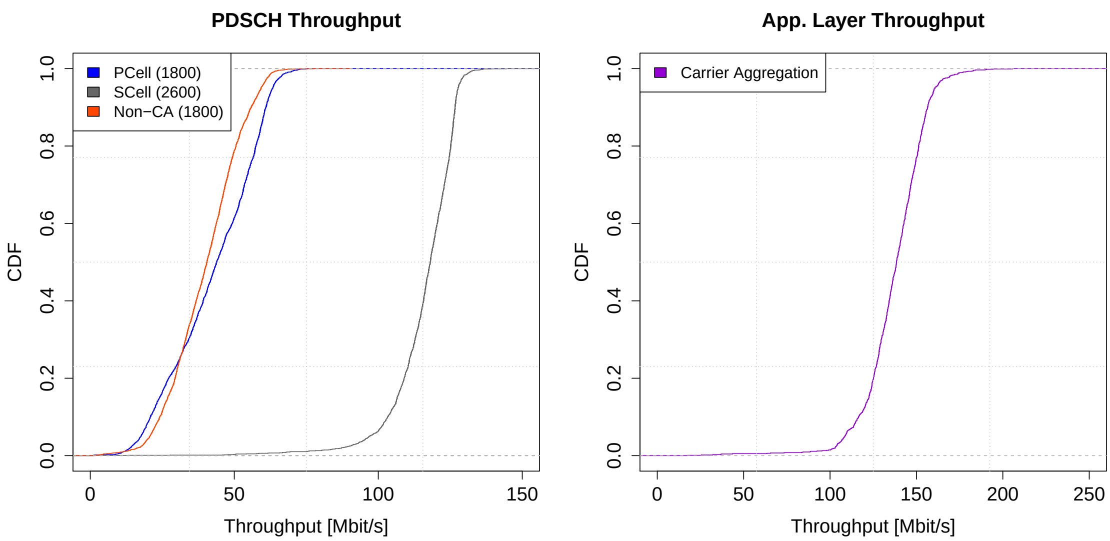


Figure 29: Measurement location C: PDSCH and Application throughput

The peak application throughput using Carrier Aggregation was 205.6 Mbit/s and for the non-CA UE 59.7 Mbit/s. As in the measurement location B, CA-capable UE can utilize secondary carrier with less interference, which is capable of providing improved throughput compared to primary carrier. In the measurement location C, Carrier Aggregation provides 244 % performance gain in peak throughput compared to non-CA UE.

Measurement location C demonstrates the importance of careful frequency planning. The performance of 1800 MHz could be improved with smaller cell coverage areas and with Inter-Cell Interference Coordination (ICIC) methods. An unused frequency, such as 2600 MHz in this situation, offers greater performance gain than two carriers at the existing 1800 MHz frequency would have. The behavior in measurement location C was rather extreme. However, such behavior is possible in practical networks as new carrier frequencies are deployed during LTE-A network roll-out. The performance gain achieved in measurement location C is clearly visible for the users as well.

5.3.4 Indoor Throughput Measurement

The most obvious benefit of Carrier Aggregation is the improved throughput. The indoor throughput measurement was conducted to test the indoor performance in excellent radio conditions. The objective was also to find the best achievable data rate in CA. Both carriers experienced SNR above 25 dB. The throughput was measured from both physical and application layer. Application layer throughput corresponds to the experience of the user. The PDSCH throughput presented here is simply the sum of the throughputs of two physical layer data streams. The results are illustrated in the Table 14 and as a CDF in Figure 30. The maximum measured throughput at the application layer was 276.7 Mbit/s, while the maximum physical layer throughput was 289.7 Mbit/s. It can be noted that the peak throughput is slightly smaller than in measurement location A.

Table 14: Indoor measurement throughputs

	Uplink	**Downlink**
Physical Layer		
Average Throughput	46.4 Mbit/s	284.5 Mbit/s
Peak Throughput	46.9 Mbit/s	289.7 Mbit/s
Application Layer		
Average Throughput	42.7 Mbit/s	259.0 Mbit/s
Peak Throughput	46.8 Mbit/s	276.7 Mbit/s

This measurement also demonstrates amount of header information in mobile packet switched data traffic. The PDSCH traffic includes the packet headers from all the above layers in user plane radio protocol stack (Section 2.4). The average difference in data rates is 9 %, which illustrates the importance of header compression methods. The same difference in uplink data rates is 8 %.

Category 6 UEs do not support uplink Carrier Aggregation [37]. That is clearly visible in Figure 30, as UL throughput is limited to 50 Mbit/s. The peak throughput in good radio conditions at the application layer was 46.8 Mbit/s.

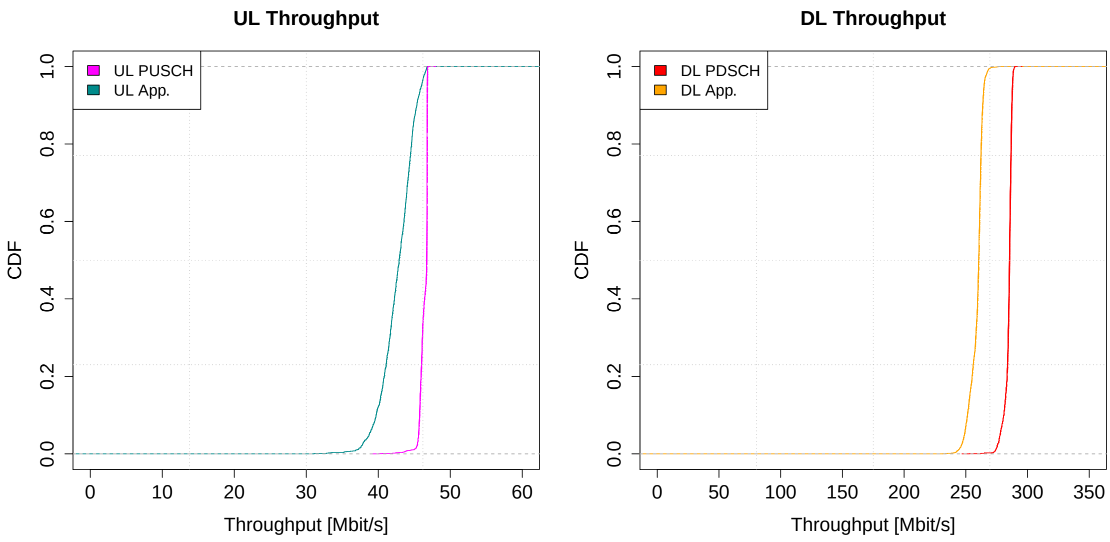


Figure 30: Physical and application layer throughputs in indoor measurement

5.3.5 Summary

The stationary measurements proved that the practical performance of Carrier Aggregation using two component carriers is close to the theoretical performance. The measured maximum throughput at the application layer was 286.8 Mbit/s. Application layer throughput is the user experienced data rate. The result is very close to the theoretical maximum of 300 Mbit/s for 2×2 MIMO and 2×20 MHz bandwidth. Such results can be achieved in excellent radio conditions.

Carrier Aggregation improves the performance also at the cell edge. In a scenario, where both frequencies are deployed in a macro base station and have similar coverage areas, the user at cell edge is able to receive data through both cells. The performance gain at cell edge is up to 127 %. In this case, the secondary carrier had significantly better SNR levels. Table 15 summarizes the peak throughputs and CA performance gains from different stationary measurement locations.

Table 15: Peak throughputs and CA performance gains

	Without CA	**With CA**	**Gain**
Location A: *Good radio conditions*	142.9 Mbit/s	286.8 Mbit/s	101 %
Location B: *Poor radio conditions*	27.3 Mbit/s	61.9 Mbit/s	127 %
Location C: *Average radio conditions*	59.7 Mbit/s	205.6 Mbit/s	244 %

The SNR caused performance difference between the frequencies was amplified in measurement location C. As the other frequency (1800 MHz) suffered from interference, the cell performance decreased. While the 2600 MHz frequency had lower signal strength, it had excellent SNR conditions as it was otherwise unused in the area. The non-CA UE selected the serving cell on RSRP basis and was limited to maximum throughput of 59.7 Mbit/s. The CA capable UE was able to utilize also the unused 2600 MHz band and received throughput of 205.6 Mbit/s in measurement location C.

Currently, there are no uplink CA-capable UEs available. The present downlink CA implementation provides no improvement to the uplink throughput as demonstrated in Table 14 and in Figure 30.

5.4 Mobility Measurements

Carrier Aggregation introduces changes in LTE mobility and cell management. CA can be utilized after SCell configuration. [7] The SCell needs to be configured in case of data service initiation and after handover. To understand the CA operation, these procedures are further analyzed in Section 5.4.1 and in Section 5.4.3. Furthermore, the delay in SCell configuration after service request and intra-eNodeB handover was measured in Sections 5.4.2 and 5.4.4. The objective was to determine whether the delays affect the user experience. The network configuration did not provide possibility to test the SCell change via A6 event. The event is most likely to occur in CA deployment scenarios 3 and 4, which were illustrated earlier in Figure 14.

5.4.1 SCell Configuration Trace

Carrier Aggregation setup for data transmission requires configuration of the secondary carrier for the UE. The procedure from UE initiated service request to enabled CA is depicted in this section. *Nemo Handy* was used to trace the signalling messages between UE and the eNodeB. The RRC messages follow Release 10 specification. In this example, the PCI of PCell is 1 and it is at 2600 MHz band. The added SCell has PCI 43 and it is at 1800 MHz band.

Figure 31 presents the trace of Layer 3 signalling message flow during the connection setup and SCell addition for UE.

Event ID	System	Transf. dir.	Time	Sub channel	Message name
L3SM	LTE FDD	Uplink	13:48:53.129		SERVICE_REQUEST
RRCSM	LTE FDD	Uplink	13:48:53.130	CCCH	RRCConnectionRequest
RRCSM	LTE FDD	Downlink	13:48:53.204	CCCH	RRCConnectionSetup
RRCSM	LTE FDD	Uplink	13:48:53.208	DCCH	RRCConnectionSetupComplete
RRCSM	LTE FDD	Downlink	13:48:53.231	DCCH	SecurityModeCommand
RRCSM	LTE FDD	Downlink	13:48:53.232	DCCH	RRCConnectionReconfiguration
RRCSM	LTE FDD	Uplink	13:48:53.232	DCCH	SecurityModeComplete
RRCSM	LTE FDD	Uplink	13:48:53.238	DCCH	RRCConnectionReconfigurationComplete
RRCSM	LTE FDD	Downlink	13:48:53.252	DCCH	RRCConnectionReconfiguration
RRCSM	LTE FDD	Uplink	13:48:53.255	DCCH	MeasurementReport
RRCSM	LTE FDD	Uplink	13:48:53.267	DCCH	RRCConnectionReconfigurationComplete

Figure 31: SCell configuration signalling message flow in connection setup

1. To establish downlink data connection UE sends SERVICE_REQUEST to the eNodeB. The subsequent *RRCConnectionRequest* is sent via CCCH. The message is presented below. It includes the *ue-Identity* and indicates that the cause for connection request is mobile originated.

```
RRCConnectionRequest     (3GPP TS 36.331 ver 10.6.0 Rel 10)

UL-CCCH-Message
  message
    c1
      rrcConnectionRequest
        criticalExtensions
          rrcConnectionRequest-r8
            ue-Identity
              s-TMSI
                mmec
                  Bin     : 1B  (= 27)
                m-TMSI
                  Bin     : E0 F8 7B E4  (32 bits)
            establishmentCause     : mo-Data
            spare
              Bin     : 0 (1 bits)
```

2. eNodeB informs the necessary parameters for connection setup via *RRC-ConnectionSetup* message. The setup configures a dedicated control channel (DCCH) for further signalling, connected state parameters and offsets for CQI and RI, and the transmission mode to be used.
3. UE makes the required changes and signals the completion with *RRCConnectionSetupComplete* using DCCH.
4. Network assigns UE with encryption keys for transmission with *SecurityModeCommand*. UE responds with *SecurityModeComplete*.
5. *RRCConnectionReconfiguration* message configures necessary measurement parameters and radio bearers for the UE. The UE is commanded to measure two LTE carriers, in this example EARFCN 3100 and EARFCN 1300. They both employ the carrier frequency of 20 MHz (i.e. 100 PRBs). UE confirms the command with *RRCConnectionReconfigurationComplete* message to the eNodeB. UE is now in RRC_CONNECTED state and is capable of receiving user plane data.

```
rrcConnectionReconfiguration-r8
  measConfig
    measObjectToAddModList
      measObjectToAddModList value 1
        measObjectId     : 1
        measObject
          measObjectEUTRA
            carrierFreq     : 3100
            allowedMeasBandwidth     : mbw100
            presenceAntennaPort1     : true
            neighCellConfig
              Bin     : 0 (2 bits)
      measObjectToAddModList value 2
        measObjectId     : 2
        measObject
          measObjectEUTRA
```

```
carrierFreq     : 1300
allowedMeasBandwidth     : mbw100
presenceAntennaPort1     : true
neighCellConfig
  Bin     : 0 (2 bits)
measCycleSCell-r10     : sf320
```

6. UE measures the defined carriers and sends *MeasurementReport* to the eNodeB. The report indicates that there is a potential secondary carrier available with good signal strength.
7. If the eNodeB is CA capable, it sends another *RRCConnectionReconfiguration* command to the UE. It includes specific *sCellToAddModList* command that configures new Secondary Cell along with additional radio bearer configuration. The crucial parameters are *sCellIndex* (1), *physCellId* (PCI 43), *dl-CarrierFreq* (EARFCN 1300) and *dl-Bandwidth* (100 PRBs). In other words, the first secondary cell is added for the UE. It resides in 1800 MHz band and can utilize bandwidth of 20 MHz.
8. UE activates the RF parts for the other frequency and establishes the radio bearers. After that, UE sends *RRCConnectionReconfigurationComplete* to the eNodeB. As a result, SCell has been successfully added for the UE. Typically, the SCell configuration takes additional 30 ms on top of Release 8 connection setup. In this example, the SCell addition delay is 29 ms.

```
nonCriticalExtension
  sCellToAddModList-r10
    sCellToAddModList-r10 value 1
      sCellIndex-r10     : 1
      cellIdentification-r10
        physCellId-r10     : 43
        dl-CarrierFreq-r10     : 1300
      radioResourceConfigCommonSCell-r10
        nonUL-Configuration-r10
          dl-Bandwidth-r10     : n100
          antennaInfoCommon-r10
            antennaPortsCount     : an2
          phich-Config-r10
            phich-Duration     : normal
            phich-Resource     : oneSixth
          pdsch-ConfigCommon-r10
            referenceSignalPower     : 17
```

According to this example trace, the connection setup takes 109 ms and the SCell configuration takes 29 ms on top of that. The SCell addition delay is further examined in the next section.

5.4.2 SCell Configuration Delay

To further evaluate the SCell configuration procedure, the time between user requesting a data transfer and the moment another component carrier is configured for the user should be investigated. The delay can be estimated from control plane, mainly RRC layer, messages exchanged between eNodeB and UE. SCell configuration delay was measured from the UE triggered SERVICE_REQUEST message to the particular *RRCConnectionReconfigurationComplete* message that confirms SCell addition. The messages were already visualized in Figure 31.

The overall connection setup delay from SERVICE_REQUEST message to SCell addition is illustrated in Figure 32. The average SCell configuration delay was 142 ms. The variation is rather low.

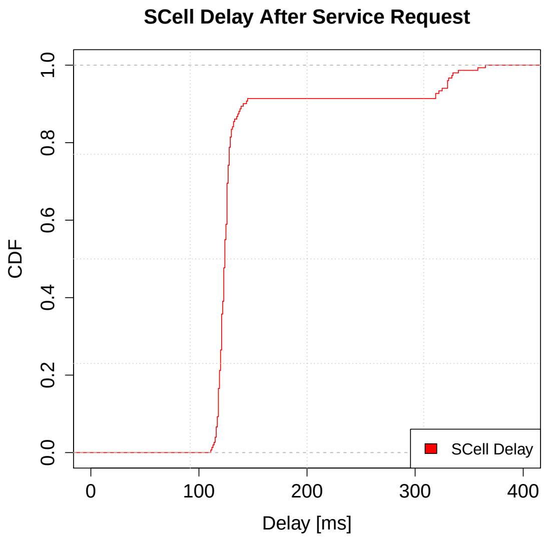


Figure 32: SCell activation delay after service request from the UE

However, few of the service request procedures included additional Authentication and Security Mode procedure to identify the UE. The EPC initiates this procedure in approximately 5 % of the service requests and it adds 150–200 ms to the entire service request procedure. To UE it appears as a downlink AUTHENTICATION_REQUEST message. Without the Security Mode procedure the average SCell configuration delay would have been smaller. The procedure is nevertheless present in practical networks.

From the UE point of view, the user plane for data connection has been established after the first *RRCConnectionReconfigurationComplete* message. That involves setting up required radio bearers. The core network should start forwarding data through serving cell towards UE shortly after that.

In practice, the delay in configuring SCell is not visible to the user. In most cases, the entire connection setup procedure in LTE is completed almost immediately. However, from the network point of view, shorter delay improves the overall performance. It can be observed that apart from the authentication requests, the variance in setup procedure is rather low. Approximately 95 % of the data connection establishments are performed within a 100–150 ms timeframe. To the user, the connection setup with CA appears as fast as with Release 8 LTE.

5.4.3 Handover Trace

Another procedure after which SCell has to be configured is handover. The operation is presented in this section. Once again, *Nemo Handy* was used to trace the signalling messages between UE and the eNodeB. The PCells are located at 2600 MHz frequency and the SCells are at 1800 MHz frequency. The source cell and target cell refers to the two primary cells. The source cell PCI is 1, and the target cell PCI is 2.

Figure 33 presents the trace of Layer 3 signalling message flow between UE and eNodeBs during the CA handover. The Release 8 intra-LTE handover procedure is described in more detail in Section 2.6.

Event ID	System	Transf. dir.	Time	Sub channel	Message name
RRCSM	LTE FDD	Uplink	13:42:09.048	DCCH	MeasurementReport
RRCSM	LTE FDD	Downlink	13:42:09.070	DCCH	RRCConnectionReconfiguration
RRCSM	LTE FDD	Uplink	13:42:09.091	DCCH	RRCConnectionReconfigurationComplete
RRCSM	LTE FDD	Downlink	13:42:09.116	DCCH	RRCConnectionReconfiguration
RRCSM	LTE FDD	Uplink	13:42:09.118	DCCH	RRCConnectionReconfigurationComplete
RRCSM	LTE FDD	Downlink	13:42:09.120	BCCH-SCH	SystemInformationBlockType1
RRCSM	LTE FDD	Uplink	13:42:09.147	DCCH	MeasurementReport
RRCSM	LTE FDD	Downlink	13:42:09.171	DCCH	RRCConnectionReconfiguration
RRCSM	LTE FDD	Uplink	13:42:09.187	DCCH	RRCConnectionReconfigurationComplete

Figure 33: Handover signalling message flow with SCell reconfiguration

1. In RRC_CONNECTED state, the eNodeB begins preparation for handover after receiving *MeasurementReport* from the UE via DCCH indicating certain measurement event threshold has been triggered. In this case, the measurement event A3 (see Table 2) has triggered, indicating that neighboring cell has became offset better than PCell. Here, RSRP of the PCell is -90 dBm and RSRP of neighboring cell is -84 dBm, while the offset in the network was defined to 4 dB. Also, the SCell is measured and reported. However, the SCell result does not affect on handover decision. An extract from the *MeasurementReport* is presented below.

```
measurementReport-r8
  measResults
    measId      : 1
    measResultPCell
      rsrpResult      : 50
      rsrqResult      : 10
    measResultNeighCells
      measResultListEUTRA
        measResultListEUTRA value 1
          physCellId      : 2
          measResult
            rsrpResult      : 56
            rsrqResult      : 19
    measResultServFreqList-r10
      measResultServFreqList-r10 value 1
        servFreqId-r10      : 1
        measResultSCell-r10
          rsrpResultSCell-r10      : 60
          rsrqResultSCell-r10      : 9
```

2. If the source eNodeB decides to perform handover, it sends handover request to the target eNodeB. In case of intra-LTE handover, the UE is always allowed to connect if there are sufficient resources available. The target eNodeB sends ACK to the source eNodeB to confirm the handover.

3. After the source eNodeB receives permission for handover, it sends *RRC-ConnectionReconfiguration* message to the UE. Handover is executed with specific *MobilityControlInfo* command along with target cell PCI (2). If there are SCells configured, they are released before the handover with *sCellToReleaseList* command. It indicates the SCell index that is to be released (1).

```
DL-DCCH-Message
  message
    c1
      rrcConnectionReconfiguration
        rrc-TransactionIdentifier     : 1
        criticalExtensions
          c1
            rrcConnectionReconfiguration-r8
              mobilityControlInfo
                targetPhysCellId     : 2

              nonCriticalExtension
                nonCriticalExtension
                  nonCriticalExtension
                    sCellToReleaseList-r10
                      sCellToReleaseList-r10 value     : 1
```

4. During handover, the source eNodeB forwards UE data to the target eNodeB. UE detaches itself from the source eNodeB and synchronizes with the target eNodeB. After UE has configured the target eNodeB specific parameters, it responds with *RRCConnectionReconfigurationComplete* message to the target eNodeB to finalize the radio handover. In this case, the handover delay is 21 ms. Now, UE can continue user plane data exchange with the target eNodeB.

5. The target cell configures the required measurements for UE with another *RRCConnectionReconfiguration* message. Here, the same objects are measured in the target cell. UE confirms the configuration with *RRCConnectionReconfigurationComplete* message.

6. The target eNodeB broadcasts the cell specific information using System Information Blocks (SIB). UE reads *SystemInformationBlockType1* message from BCCH, which defines e.g. the cell ID, tracking area code and mapping for other SIB messages. The UE receives more SIBs shortly after the handover is complete and they include information e.g. on power control and neighbor cells.

7. The target cell receives *MeasurementReport* from the UE via uplink DCCH. UE reports that there is a neighboring cell at the PCell frequency. The neighboring cell is the previous serving cell with PCI 1. However, the current serving cell has better signal strength and therefore no further action is needed.

8. The eNodeB commands UE to add SCell using *RRCConnectionReconfiguration* message. It includes specific *sCellToAddModList* command that configures new secondary cell along with required radio bearer configuration. The essential parameters are *sCellIndex* (1), *physCellId* (PCI 44), *dl-CarrierFreq* (EARFCN 1300) and *dl-Bandwidth* (100 PRBs). The cell has possibility to use two antenna ports, i.e. it is 2×2 MIMO capable. Now, the secondary cell is reconfigured for the UE.

```
sCellToAddModList-r10
  sCellToAddModList-r10 value 1
    sCellIndex-r10     : 1
    cellIdentification-r10
      physCellId-r10     : 44
      dl-CarrierFreq-r10     : 1300
    radioResourceConfigCommonSCell-r10
      nonUL-Configuration-r10
        dl-Bandwidth-r10     : n100
        antennaInfoCommon-r10
          antennaPortsCount     : an2
        phich-Config-r10
          phich-Duration     : normal
          phich-Resource     : oneSixth
        pdsch-ConfigCommon-r10
          referenceSignalPower     : 17
```

9. UE activates the RF parts for the other frequency and establishes the radio bearers. After that, UE sends *RRCConnectionReconfigurationComplete* to the eNodeB. As a result, SCell has been successfully added for the UE. In this example, the SCell configuration took 96 ms after the handover was completed.

5.4.4 Handover Delay

The intra-LTE handover is specified to be a fast operation. The maximum interruption in user plane data connection should be less than 65 ms. [26] The handover interruption is studied in this measurement and it can be concluded that the requirement is typically fulfilled easily. However, the SCell configuration after handover causes some delay in CA operation. As discovered in the previous section, the secondary cells are disabled for the duration of the handover. Therefore, they have to be reconfigured after the handover is otherwise completed. In this measurement, this delay is evaluated and determined whether it affects the user experience.

The delay in SCell configuration in this measurement is defined as the time between *RRCConnectionReconfigurationComplete* message that completes the handover and the *RRCConnectionReconfigurationComplete* message that confirms the SCell addition for the UE. The delay is measured from the RRC message time stamps. Both handover delay and the cumulation of handover delay and SCell addition is presented in Figure 34.

In the measurement all handovers were intra-eNodeB handovers. The average handover delay is 21 ms, while the average SCell configuration delay including handover is 92 ms. Major share of the samples are less than 100 ms from the handover. The user cannot notice the difference and CA connectivity seems to be seamless.

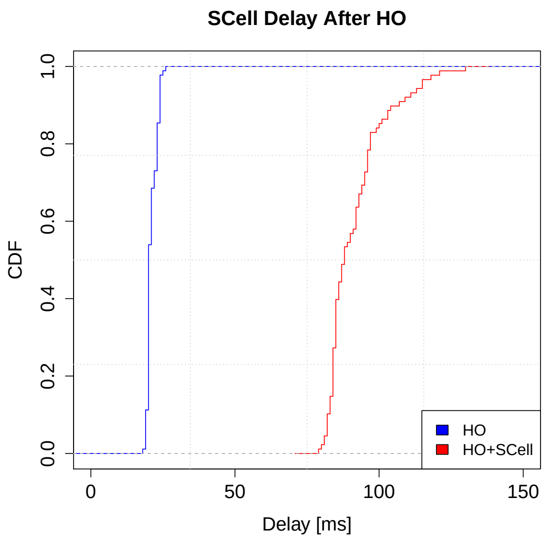


Figure 34: Handover delay with and without SCell configuration

5.4.5 Pedestrian Mobility Measurement

The impact that radio conditions possess on user experienced throughput were studied. The motivation was to study the effect that signal strength and quality have on performance. Hypothetically, the performance improves in good radio conditions and vice versa. Therefore, a mobility measurement was conducted in order to collect measurement samples in various radio conditions. The correlation (Equation 3) between radio conditions and throughput was analyzed afterwards. It is also possible to determine approximate conditions in which the peak throughputs can be achieved.

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{3}$$

Pedestrian mobility measurement was performed in the proximity of the eNodeB in Figure 20. The measurement duration was approximately 30 minutes. During the measurement, a large text files were transferred from FTP server. The PDSCH throughput of the transfers were recorded. The measured throughput samples were mapped with the corresponding RSRP and SNR samples, which were then plotted into a scatter chart. The results are presented in Figures 35 and 36. The correlations between throughput and RSRP/SNR are presented in Table 16.

Table 16: Correlation of througput vs RSRP and SNR

	RSRP		**SNR**	
Frequency	2600 MHz	1800 MHz	2600 MHz	1800 MHz
Correlation	0.608	0.529	0.868	0.717

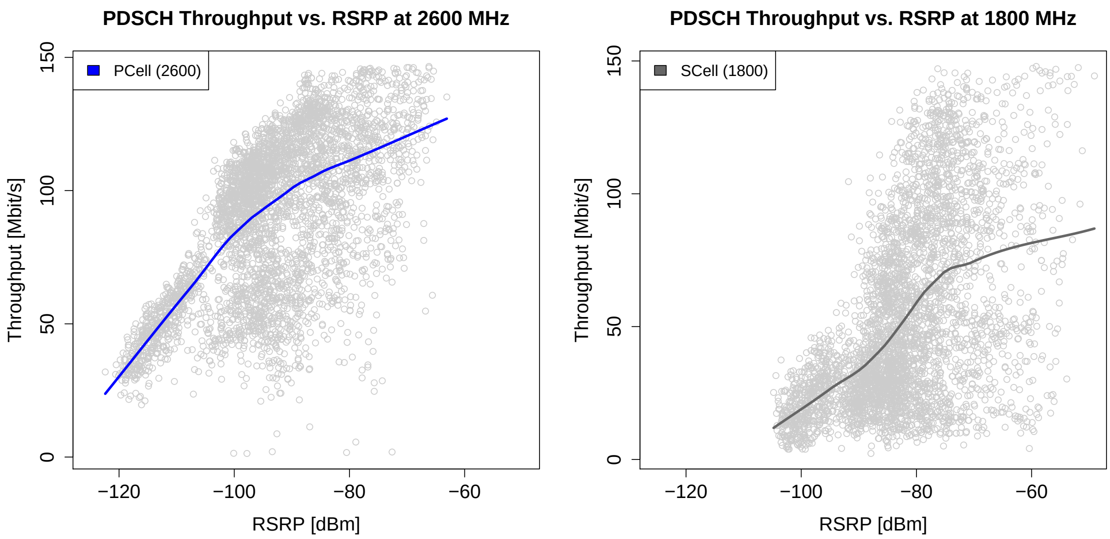


Figure 35: PDSCH throughput and corresponding RSRP

From the Figure 35 it can be noted that RSRP has positive correlation to the throughput. Namely, 0.608 for PCell at 2600 MHz and 0.529 for SCell at 1800 MHz. The average RSRP for 2600 MHz is -93.1 dBm and for 1800 MHz it is -82.1 dBm. In the RSRP range of -120 to -100 dBm, the throughput increases almost linearly, if the RSRP improves. The variance increases above -100 dBm. For instance, at RSRP level of -90 dBm it is possible to obtain throughput well above 100 Mbit/s, but also throughputs below 50 Mbit/s. Nevertheless, the absolute peak throughputs in the range of 150 Mbit/s can be achieved if the RSRP is above -80 dBm on either frequency. Such signal strength is relatively easy to reach in practical networks.

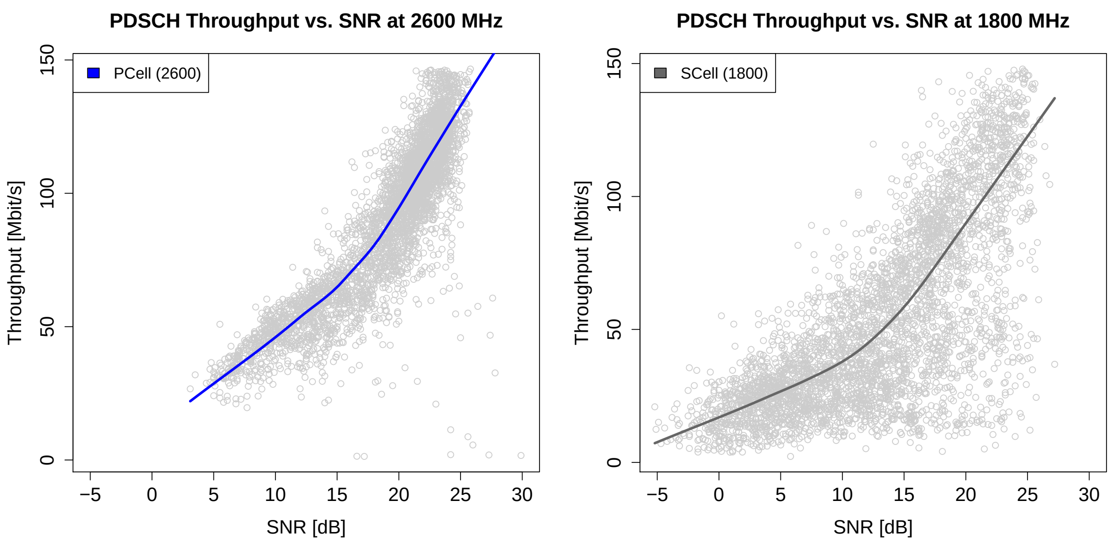


Figure 36: PDSCH throughput and corresponding SNR

The Figure 36 illustrates the correlation between SNR and PDSCH throughput. The PCell at 2600 MHz frequency experienced strong positive correlation of 0.868 between SNR and throughput. The SCell at 1800 MHz frequency experienced slightly lower positive correlation of 0.717. It can be observed that the correlation with SNR is significantly stronger than with RSRP. It should be noted that the cell load affects SNR, which is reduced in high load situation. The average SNR for 2600 MHz is 18.8 dB and for 1800 MHz the average is 12.8 dB. The results indicate that LTE in general is more sensitive to the downlink interference than to low received signal power in downlink. The downlink throughput at 2600 MHz follows the SNR rather linearly through the measured range. At the 1800 MHz frequency the variance is greater. The peak throughputs are typically achieved if the SNR is above 20 dB.

5.4.6 Summary

The mobility measurements included signalling trace examples from SCell configuration after service request and intra-eNodeB handover. Traces demonstrated the signalling flow between UE and eNodeB during these procedures.

The main purpose for the mobility measurements was to determine whether interruption in CA operation due to additional signalling in SCell configuration is noticeable to the user. The results denote that configuring SCell within data connection setup is really swift procedure. The connection setup and SCell addition was performed in 142 ms on average. The overall results are presented in Figure 32.

The results in handover measurement indicate that the SCell configuration within handover is performed in 92 ms on average. The interruption in data connection (the actual handover) is conducted in 21 ms on average. The results are presented in Figure 34. Both operations are fast and the user cannot notice the additional delay in CA connection.

Additionally, the effect of changing RSRP and SNR levels on downlink throughput was studied. The results are visible in Figures 35 and 36. It was determined that high SNR level correlates more with high throughput than RSRP levels. It can be concluded that LTE in general is more vulnerable to interference than to poor signal strength. However, the radio condition requirements for high throughput are not difficult to achieve. The SNR level above 20 dB and RSRP level above -80 dBm should be sufficient.

5.5 Discussion

In this section, the measurements are further discussed and analyzed. The reliability of the results is under evaluation and also few proposals are made for future research.

The terminals used in the measurements were commercial mobile phones. The requirements for UE measurement accuracy are strict and there should be no differences between Cat. 4 and Cat. 6 devices. The SNR, RSRP and throughput values should be reliable and comparable. *Nemo Handy* software gathers the measurement data directly from the diagnostics port. The measurement software is highly regarded in the industry and is capable of providing accurate results.

The number of samples in the each of the stationary throughput measurements was more than 2000. In that sense, the results should be fairly reliable. In live network measurement, there typically is some variance in radio conditions, due to fading and reflections [14]. Some variance occurs even if the location is stationary. The final results and figures include also the throughput ramping phase at the beginning of data transfer. The number of samples in mobility measurements was considerably less. The SCell configuration delay measurement in Section 5.4.2 consisted of 151 UE initiated data transfers and the handover delay measurement in Section 5.4.4 consisted of 88 handovers. While, the accuracy could be improved with greater number of samples, the mean delay would assumedly remain the same.

It is worth remembering that in all measurements the 2600 MHz frequency was rather isolated and it experienced only a fraction of the interference when compared to 1800 MHz frequency. This situation occurs in the early phase of CA deployment as an unused carrier frequency provides more than 100 % performance gain. Furthermore, the network was practically non-congested during the measurements. It would have been interesting to test the load balancing features, if there were more simultaneous active users in the eNodeB. However, it was not feasible to artificially generate more traffic to the network. That could be a subject for a future study.

The network setup did not offer the possibility to test inter-eNodeB handover in CA. The comparison between intra-eNodeB and inter-eNodeB handovers would have been useful and interesting. There were neither the possibility to test the new A6 measurement event as it would have required a small cell or RRH inside the macro cell. These tests should also be considered in the future.

In a simulation study by Shayea et al [44], the user throughput improved everywhere in the cell coverage area when CA was used and additional carriers were deployed. The combination of 5×20 MHz component carriers provided average throughput of 94 Mbit/s and 1×20 MHz provided 12 Mbit/s. Furthermore, the CA implementation increases the system capacity in terms of active users per cell. The capacity increment was rather linear. In another simulation study [45], Almesaeed et al have concluded that inter-cell interference decreases the overall system performance in LTE-A networks. That should be considered in all performance evaluations. According to their simulation results, the inter-band CA does not offer any additional gain compared to intra-band CA.

In the field measurements conducted by Werner et al [46], it was observed that additional MIMO layers increase the throughput significantly. For instance, 3×20 MHz with 8×8 MIMO provides maximum throughput of 1 Gbit/s, which fulfills the IMT-Advanced requirement for low mobility [27]. The test was conducted in interference free and isolated environment, using 2700 MHz band. The drive tests by Nokia [33] show that 2×20 MHz CA is capable of providing 250–300 Mbit/s downlink throughput.

The previous studies have already proven the potential and performance of Carrier Aggregation. This research provided one of the first published CA performance measurements in commercial network. In general, the results are in line with the simulation studies and the theoretical expectations.

6 Conclusions

This thesis presented a study on performance of LTE-Advanced feature referred as Carrier Aggregation. The literature part gives an overall description on Long Term Evolution and the LTE-A techniques. Other LTE-A technologies include e.g. Coordinated Multipoint (CoMP) transmission and reception, improvements to operation and management of heterogeneous networks (HetNet) and the possibility to use relay nodes. The characteristics and functionalities of Carrier Aggregation are the main part of the literature review. The CA performance was evaluated with field measurements and the results are presented in this thesis.

It could be argued that the regular mobile phone user rarely transfers large files over the radio network. The data connections are typically rather short, i.e. web browsing or messaging, and with these applications the CA improved data rates probably are not important. Furthermore, the VoIP and VoLTE services do not require faster data rates. The more important requirement for them is solid QoS, which is partly ensured with sufficient capacity in the E-UTRAN. However, the CA also provides the capacity and possibilities for load balancing. The application that could utilize the improved throughput is video streaming. While, FTP transfer was used as a higher layer application in these measurements, video streaming could be considered in the future.

Wireless connections are replacing fixed connections in providing the Internet access to the user premises. Tablet and laptop users can generate significantly more traffic than mobile phone users. That creates pressure to the operator to offer high-speed data and to secure the sufficient capacity in the network. Carrier Aggregation provides a solution for both data rates and capacity.

6.1 Objectives and Results

The principal objective for the thesis was to evaluate the CA performance in live radio access network. While the performance has already been evaluated in few simulation studies and laboratory measurements, there have not been live network measurements published in the academia. The first LTE-A networks launched in 2014, which made the live network evaluation possible. The target was to measure the network from the end user perspective, using commercial user equipment. The capabilities and performance are evaluated from the perspective of a stationary LTE-A user. Additionally, the differences in mobility situations compared to Release 8 LTE were analyzed.

It can be concluded that 2×20 MHz downlink CA configuration with 2×2 MIMO and 64QAM can provide the throughput that could be expected in theory. The highest measured throughput in the application layer was 286.8 Mbit/s, while the theoretical maximum throughput for the physical layer is 300 Mbit/s. Application layer throughput represents the user experienced data rate, while physical layer throughput includes more header information. It should be noted that such data rates can be reached only in extremely good radio conditions and the network load has to be minimal. If both carriers experience good radio conditions, the performance gain from CA is approximately 100 %.

The measurements indicate that the performance gain is even higher in less ideal radio conditions. Furthermore, CA performs unexpectedly well in poor signal strength situation, if the carrier frequencies are reasonably similar. The 2600 MHz LTE carrier could act as a secondary cell in very low signal strength and provide throughput of 30 Mbit/s, which is better than most of the DSL connections. The 2600 MHz carrier experienced better SNR conditions than 1800 MHz carrier, which resulted that the CA performance gain was 127 %. The result shows that CA improves the cell edge throughput significantly. Furthermore, if the SNR conditions are more skewed, the performance gain could be even more than 200 %.

Serving cell decision is based on signal strength. In a scenario, where a carrier experiences good signal strength, but low SNR, the throughput shall be low. If the UE is configured with another component carrier with high SNR, the performance improves dramatically. Such test scenario is unlikely to be produced in isolated laboratory environment or in simulation study. The behavior could be discovered in multi-carrier live network.

Secondary cell configuration requires additional signalling. The delay in CA configuration was measured and analyzed in two common UE operations: data connection establishment and intra-LTE handover. Initially, only one serving cell is configured for the UE in data connection establishment and secondary cells are configured after connection is set up. It was discovered that the time between UE based connection request and confirmed SCell configuration is less than 150 ms in 90 % of the cases. The message exchange that configures the SCell takes approximately 30 ms. Nonetheless, the delay is such short that it is invisible to the user. Even if the user could choose whether to use CA, the delay in connection setup is not a factor.

The intra-LTE handover is a swift operation. The secondary cells are released for the duration of the handover, but reconfigured by the target eNodeB. The average delay in which both the handover and SCell configuration is performed is 92 ms. While, the handover causes always an interruption to the data connection, the user cannot notice it. The data connection continues before the SCell configuration is started and even the entire operation is completed in less than 100 ms. The SCell configuration delays after connection setup and handover are sufficiently short and will not affect the user experience. From the E-UTRAN point of view, limiting the delay is however beneficial. Additionally, it was determined that SNR has more impact on downlink throughput than RSRP. This was confirmed in a mobility measurement where the radio conditions varied greatly within one eNodeB coverage.

6.2 Future Work

These measurements were conducted in two component carrier LTE-A network using 1800 MHz and 2600 MHz carriers. Networks that support three carriers are already emerging and more will be deployed in the near future. Testing 3CC system would be the clear next item to study in CA. More carriers create more scenarios for cell management and load balancing, and there should be more possibilities for network optimization. 3GPP is currently working on specifying more than five component carriers for CA. The network diversity will increase and terminals need to support increasing number of frequencies and band combinations. That could probably require more specialized measurement equipment utilizing complex multi-antenna configurations.

Higher order MIMO schemes will also be implemented in the future. In downlink, the next enhancement would be 4×4 MIMO, which would improve the data rates even further. The MIMO is yet to be implemented in uplink and at least a comparison between different transmission schemes should be conducted. However, the size of terminals limit the possibilities in applying spatial multiplexing.

Carrier Aggregation using small cells is another obvious area for future research. As illustrated in Section 4.2, remote radio heads can be used to provide additional capacity in hot spots. More heterogeneous network would create interesting coverage optimization problems and field testing scenarios. Additionally, if the small cells had overlapping coverage areas, the A6 measurement event could be employed and its performance be measured.

Uplink CA has not been implemented in commercial devices at the time of writing this thesis. Category 7 UE is required to support two component carrier transmission in uplink. The power management issues require more research and development from the terminal vendors. However, the uplink CA behavior is also interesting from the system performance point of view. The behavior in uplink mobility situations with CA would also offer attractive study items.

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